Research Report 2017-03
Civil & Natural Resources Engineering

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

ANALYSIS OF WATER QUALITY AND FLOW DATA FOR THE ADDINGTON CATCHMENT (2015-2016)

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ISSN 1172-9511

UC ENGINEERING

March 2017

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Report prepared for Environment Canterbury
Reviewed by Michele Stevenson

Report No: 2017-03
ISSN: 1172-9511

ABSTRACT

Addington Brook is a stormwater-influenced Christchurch waterway. Substantial instream surface water quality monitoring has shown elevated solids, metal and nutrient concentrations along the brook, which is thought to be a major contributor of these pollutants to the Avon River/Ōtākaro system and downstream estuary. Longitudinal and spatial patterns of water quality within the catchment were investigated from four wet weather events sampled in the spring-summer of 2015-2016. Analysis included assessment of treatment performance of the KiwiRail Stormwater Ponds (Matipo Street ponds) at the top of the catchment. Sites throughout the catchment responded in similar magnitudes to rainfall, with higher water levels measured from stormwater runoff shortly after rainfall was recorded. Similar inflow and outflow water levels in the Matipo ponds indicate that the detention system is mitigating peak inflows to some extent. Large amounts of TSS enter Addington Brook downstream just before it converges with the Avon River/Ōtākaro so targeting pollutant mitigation at this point could substantially reduce the amount of solids entering the Avon River/Ōtākaro. Dissolved zinc is consistently and highly elevated above the relevant Land and Water Regional Plan (LWRP) in-stream guideline, despite the pond's ability to retain large portions of it and should be targeted at the Deans Ave location where its concentration is consistently highest. Dissolved copper was effectively removed within the pond system and is not an apparent cause for concern further down-stream in this catchment. More metals were removed in the ponds, in all sampling years, when concentrations were greatest indicating that the capacity of the system does not appear to be exhausted. Given the ubiquitous nature of dissolved zinc in Christchurch urban waterways, it would be wise to implement source-control of this highly bioavailable metal, especially given dissolved fractions are much more difficult to remove than particulate fractions. Concentrations of TN (predominantly TKN) and of TP (predominantly particulate) between sampling locations are generally similar. Some nutrients are retained within the Matipo pond system although inorganic nitrate/nitrate concentrations in the outflow were higher during larger rainfall durations and depths, suggesting that nitrogen in the pond was converted from organic to inorganic fractions. TN and nitrate removal efficiencies seem to have decreased compared to estimates in 2008. Despite the ability of the ponds to significantly reduce net phosphorus overall, DRP concentrations consistently exceeded the LWRP guideline. Although solids concentrations were often very high in the stormwater, the ponds were quite effective at reducing these concentrations, which is most likely attributed to adequate settling potential within the ponds. Dissolved metal loads for the downstream site at Riccarton Ave measured during the four sampled events, were very similar to modelled loads. Overall, 2.3-2.8 kg dissolved Zn/event originate from impermeable surfaces (which comprise 79% roofs, 12% carparks, 9% roads) within the catchment while 45-84 g dissolved Cu/event originate from impermeable surfaces (39% carparks, 30% roads, 31% roofs).

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1. Introduction

Impermeable urban surfaces such as roads, carparks and roofs contribute pollutants via untreated stormwater runoff to urban waterways, causing a wide range of adverse effects on the aquatic ecosystem. Total suspended sediment (TSS), metals such as copper (Cu) and zinc (Zn), and nutrients, have been identified as the key pollutants of concern in urban waterways. Addington Brook is a stormwater-influenced stream that feeds into the Avon River/Ōtākaro near the Christchurch Hospital. Substantial instream surface water quality monitoring has shown elevated solids, metal and nutrient concentrations along the brook, which is thought to be a major contributor of these pollutants to the Avon River/Ōtākaro system and downstream estuary. Detailed modelling and investigation of the sources and character of solids and metals within this catchment has recently been reported (Charters, 2016) while comprehensive long-term surface water quality monitoring for many Christchurch waterways, including parts of the Addington Brook, are also reported in Margetts and Marshall (2015, 2016).

This study analysed wet weather water quality (and some flow data) of the Addington Brook at different sites along a ~3 km pathway to evaluate longitudinal spatial patterns within the catchment. The performance of the KiwiRail Stormwater Ponds within the catchment, to treat key pollutants, was also assessed and compared with performance data reported in 2009. Pollutant loads were assessed at one of the sites by comparing measured and modelled data. The Modelled Estimates of Discharges for Urban Stormwater Assessment (MEDUSA) contaminant load process model (Fraga *et al*., 2016) was employed for the modelling (Charters, 2016).

2. Materials and Methods

Addington Brook was sampled by the Environment Canterbury (ECan) Regional Council at four sites (Figure 1) in the 246 ha mixed industrial/commercial/residential catchment during four wet weather events during the spring and summer of 2015-2016 (Table 1). The Matipo Up-Stream (US) pond sampling site was used to capture mixed water quality received from roof, roads and carparks at the top of the catchment entering the first-flush wetland zone of the pond system. The Matipo Down-Stream (DS) pond sampling site was used to capture the outflow from the downstream detention pond and was used to generally evaluate the stormwater pond system's overall performance. It is noted, however, that there are a number of stormwater inputs throughout the system effectively short-circuiting the full treatment train (City Design, 1999 and EOS Ecology, 2009). The catchment upstream of the Matipo pond is largely impervious with activity mainly from the road-rail freight handling facility and neighbouring industrial/commercial activity. The pond system was designed to detain and treat (to an undefined level) 21.7 ha of runoff from the catchment, as previously detailed (City Design, 1999, EOS Ecology, 2009). The Deans Ave site captures the majority of runoff from the industrial/commercial sector within the

Addington catchment. The Riccarton Ave site is located furthermost downstream in Hagley Park, just before it enters the Avon River/Ōtākaro. Between the Deans Ave and Riccarton Ave sites there are inputs from a number of stormwater pipes draining commercial/residential land, as well as runoff from sports fields in Hagley Park.

Rainfall data were derived from records provided by the National Institute for Water and Atmospheric Research (NIWA), while water level was recorded by ECan for all sites along with flow at Riccarton Ave. Automatic samplers were employed by ECan for the sampling. Between 3 and 6 samples were taken for water quality analyses during each of the four events. The priority pollutants of focus to investigate were total suspended solids, dissolved metals and nutrient species. Comparison of pollutant concentrations between the overall inflow (Matipo US Pond) and outflow (Matipo DS Pond) was made based on samples taken approximately 5-9 minutes apart (e.g. Table A1, Appendix A). EOS Ecology (2011) suggested that hydraulic retention time in the first flush wetland basin was a matter of minutes and comparison of their pond treatment efficiencies were also based on approximately the same time intervals between inflow and outflow.

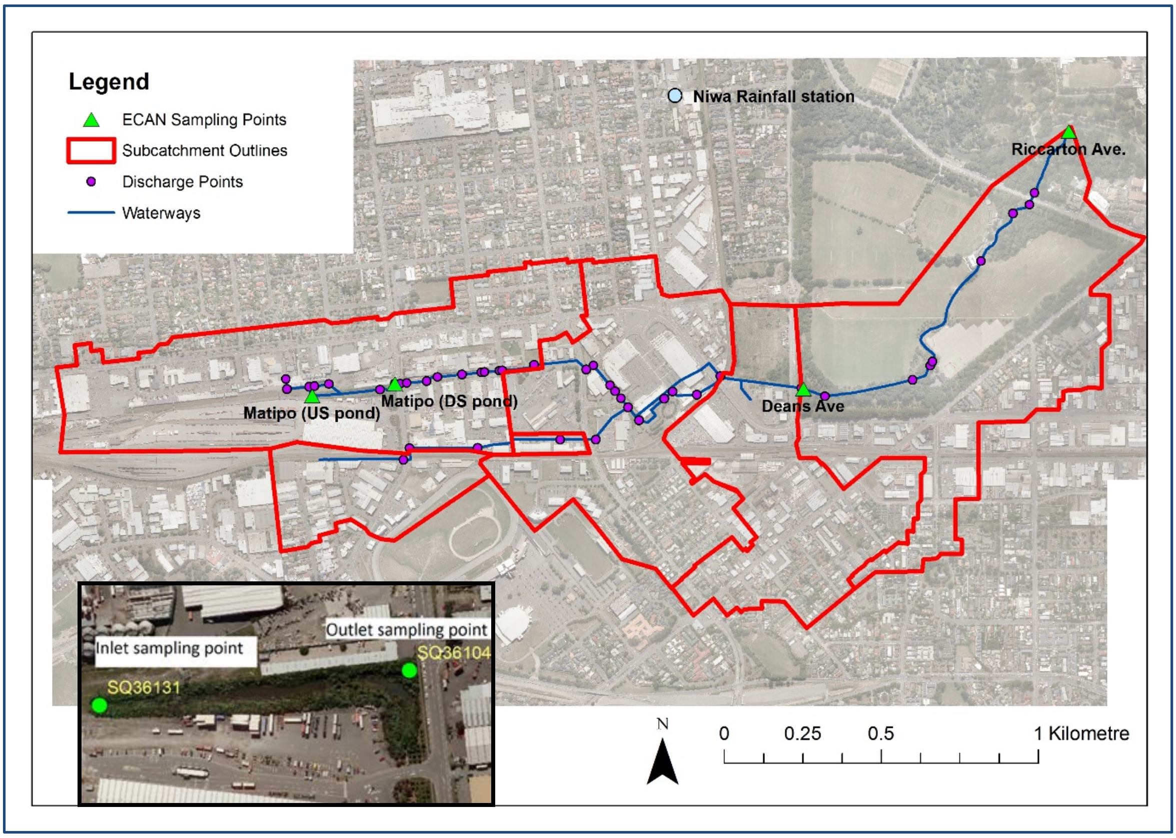


Figure 1. Sampling sites (Matipo US pond: SQ36131; Matipo DS pond: SQ36104; Deans Ave: SQ30614; Riccarton Ave: SQ34493), sub-catchments and NIWA rainfall station (Kyle Street) within the Addington catchment as delineated by the most recent GIS files available from the Christchurch City Council.

Table 1. Summary rainfall parameters for the monitored storm events. Where rainfall at the start of an event was <0.1 mm in a 5-min. interval, it was considered not an event.

Event	1	2	3	4
Date	18 to 20th Sept 2015	11 to 12th Nov 2015	15 to 16th Jan 2016	27 to 28th Jan 2016
Start	*18-09-15 19:45:00*	*11-11-15 17:45:00*	*15-01-16 19:45:00*	*26-01-16 20:45:00*
Finish	*20-09-15 10:15:00*	*12-11-15 12:15:00*	*16-01-16 09:30:00*	*28-01-16 04:45:00*
Average Intensity (mm/hr)	0.80	0.51	0.89	0.93
Peak 15-min Intensity (mm/hr)	5.72	2.48	4.44	20.48
Antecedent Dry Days (ADD)	7.82	13.19	12.07	7.55
Duration (hrs)	38.50	18.50	13.75	32.00
Total Rainfall Depth (mm)	30.67	9.40	12.20	28.30

3. Results and Discussion

3.1. Rainfall and water flow

The relationships between rainfall depth (1st y-axis) and in-stream water level (2nd y-axis) for all sampling sites and events are summarized in Figures 2-5, which also show the water quality sampling times.

At the start of a rain event, concentrations of particulate (and hence total) pollutants are often the highest as they are washed off impervious surfaces. Water sampled later in an event is usually lower in pollutant concentrations since the majority of particulate concentrations have already been washed off. However, for some dissolved pollutants (e.g. metals), concentrations may remain somewhat elevated throughout a wet weather event, depending on their origin (e.g. roof materials, roads etc). Therefore, discrete water sampling throughout a rain event is important as it captures pollutant concentrations during the characteristic rising limb, peak and receding portions of the event. This is only practically possible with an automatic sampler, given the often unpredictable nature of rain and unsocial time at which it occurs. In almost every instance, surface water was sampled throughout the rain event at all characteristic time points (with the exception of event 1 at Riccarton Ave where the peak of the event was not captured), providing important information about the range of concentrations measured throughout each event at each location (Figures 2-5).

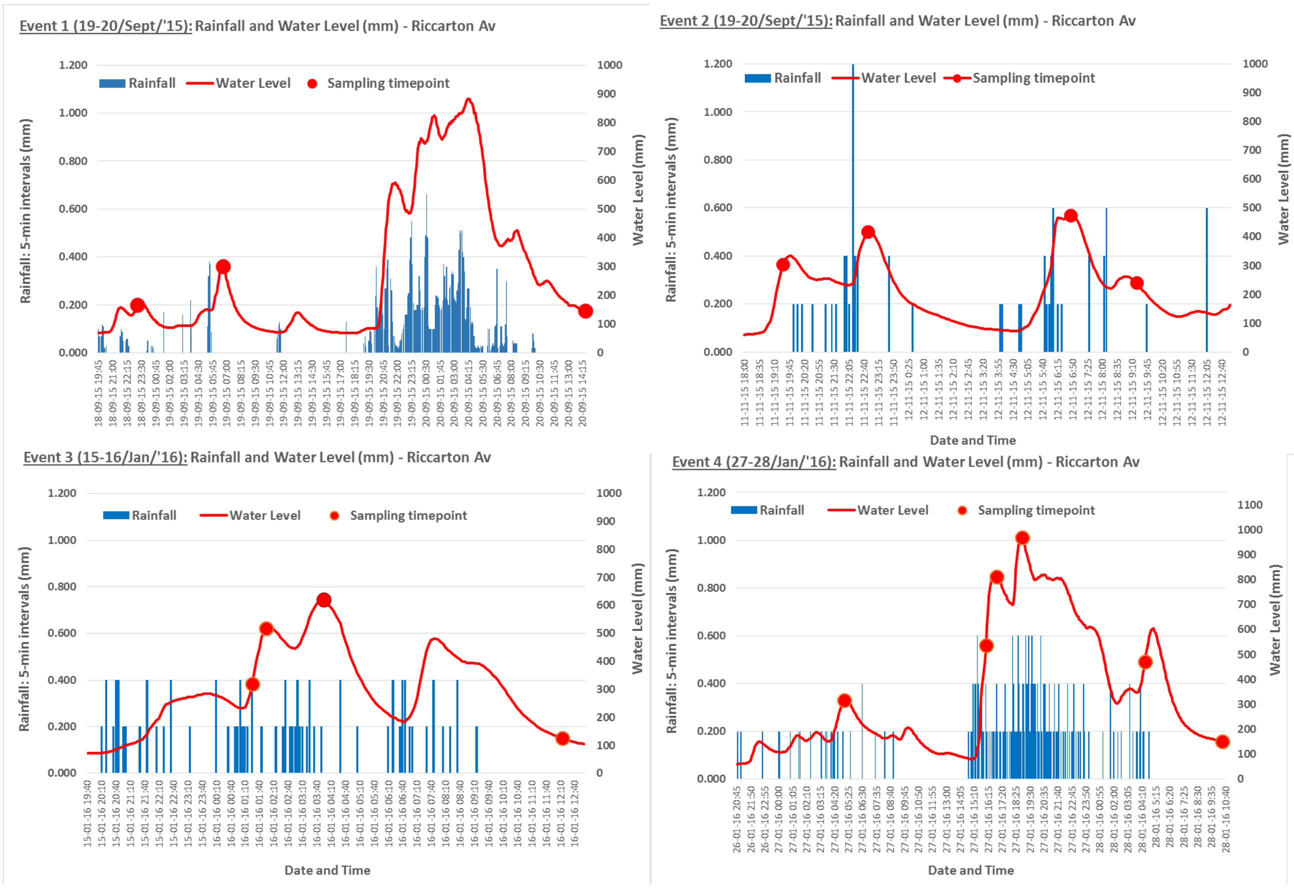


Figure 2. Relationship between rainfall depth and in-stream water level for all events at the Riccarton Ave site showing sampling times.

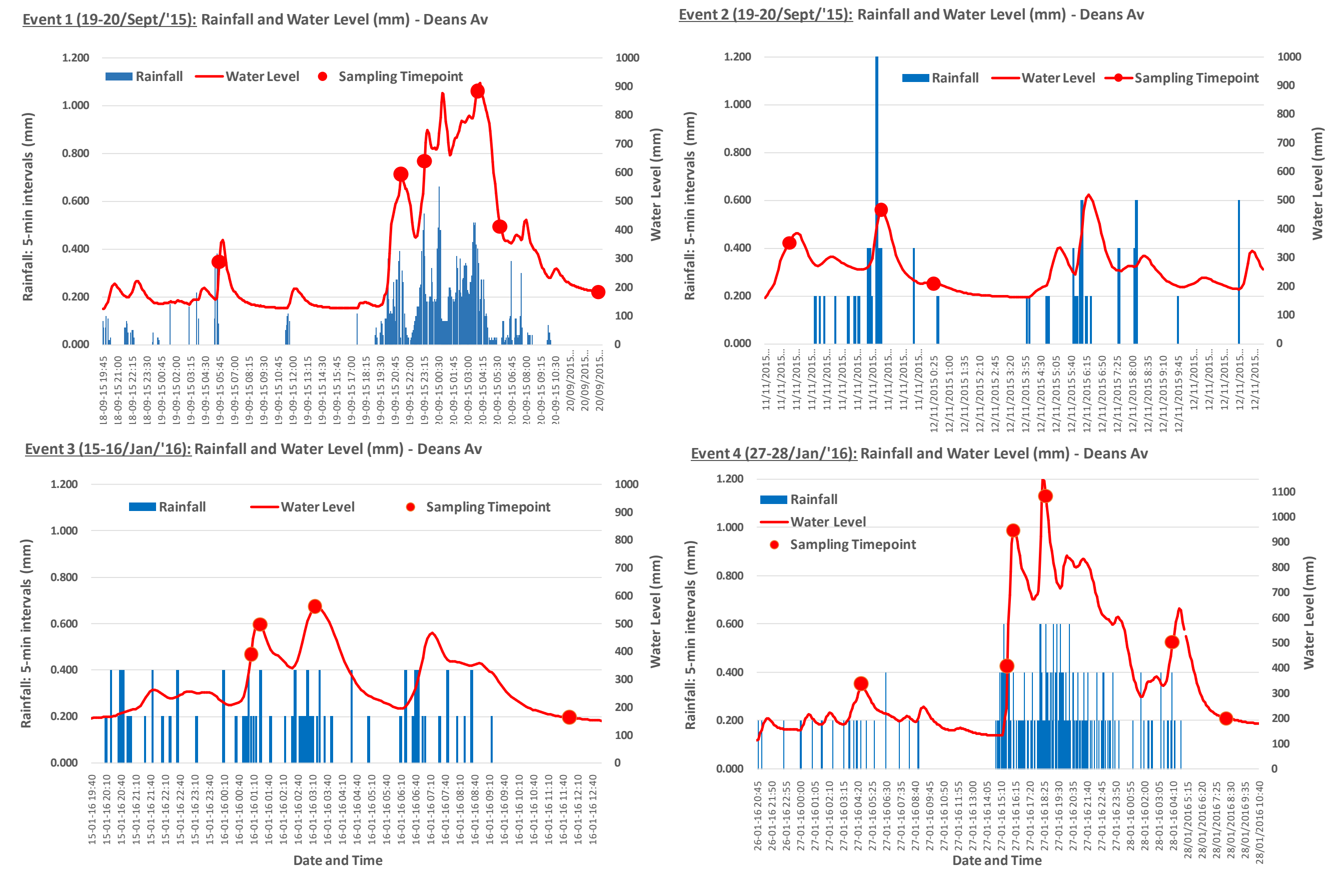


Figure 3. Relationship between rainfall depth and in-stream water level for all events atthe Deans Ave site showing sampling times.

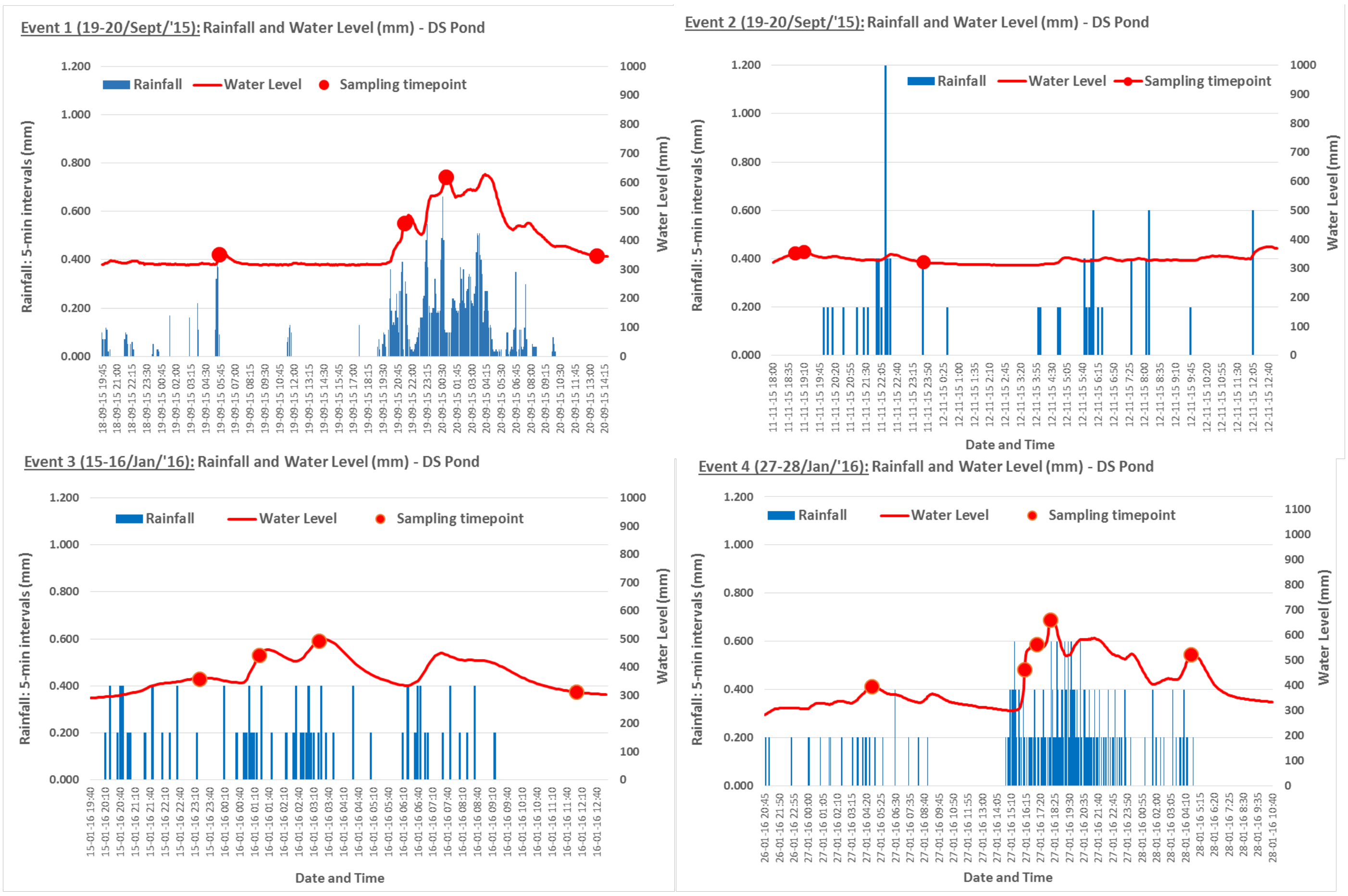


Figure 4. Relationship between rainfall depth and in-stream water level for all events at the Down-Stream Pond site showing sampling times.

Figure 5. Relationship between rainfall depth and in-stream water level for all events at the Up-Stream Pond site showing sampling times.

Overall, all sites responded in similar magnitudes to rainfall with higher water levels measured shortly after rainfall was recorded at the NIWA site, a short distance away. This response is due to stormwater runoff from the catchment conveyed directly into Addington Brook. The water levels of the up-stream (i.e. inflow) and down-stream (i.e. outflow) Matipo pond sites are quite similar, with only a few cm difference between the locations that are probably attributed to local vegetation influences or result from additional flows measured down-stream of the inflow. However, the detention system is mitigating peak inflows to some extent, especially in smaller storm events (e.g. events 2 and 3), as evident by the steady outflow water levels in Figure 4. It would be interesting to consider a pollutant tracking exercise for the pond elements to ascertain their hydraulic retention time, as this time will likely influence the amount of dissolved pollutants (metals and nutrients) that can be removed from diffuse stormwater runoff.

The relationship between rainfall depth (1st y-axis) and in-stream flow/discharge (2nd y-axis) for each sampling event at the Riccarton Ave site (the only site where this data was available) is given in Figure 6 (data for the monitoring period 18/Sep/’15-28/Jan/’16 is given in Figure B1, Appendix B).). The data clearly show how increased rainfall, contributing to increased runoff from impervious surfaces within the catchment, affects the brook’s flow rate. Events 1 and 4 had the highest peak (5-min) intensity rainfall events (5.72 and 20.48 mm/hr, respectively), as well as duration (> 30 hrs) and depth (> 28 mm) of rainfall (Table 1), which is reflected in the higher flow recorded at the Riccarton Ave site (Figure 6). The range of rainfall characteristics for this catchment in Sept-Dec 2015 are reported at peak (5-min) intensity of 0.84-31.56 (median 4.20) mm/hr, 0.7-19 (median 4.6) hrs duration and 0.3-16.26 (median 4.79) mm depth (total volume) by Charters (2016). These were noted as an unusually dry sampling period yet within the 50% annual exceedance probability (AEP) for the catchment, as predicted by the High Intensity Rainfall Design System Version 3 (HIRDS.V3) (NIWA, 2011).

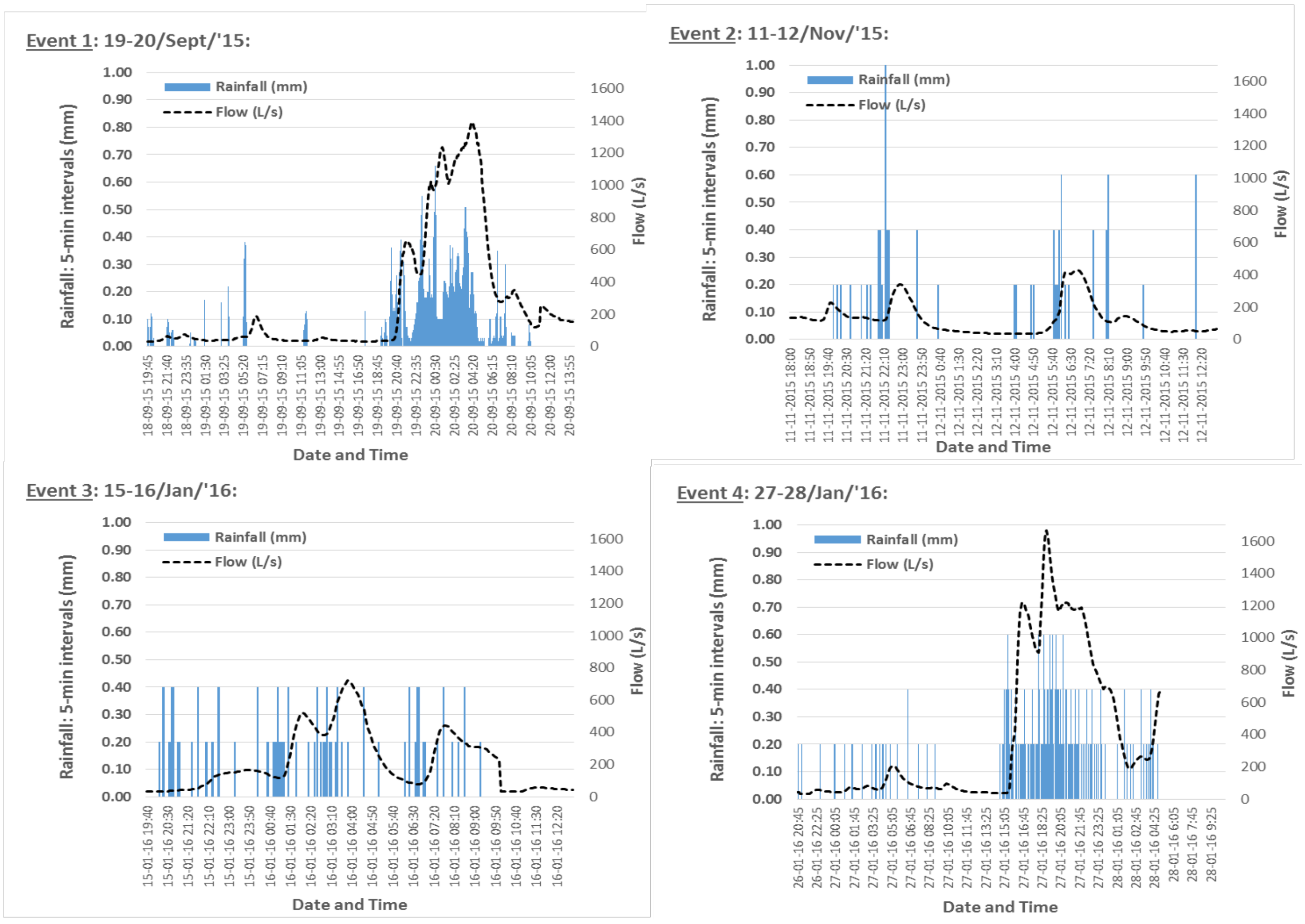


Figure 6. Rainfall and flow for Riccarton Ave for each event.

3.2. Longitudinal analysis of pollutant concentrations compared to the relevant guidelines and previous sampling data.

The water quality data for total suspended solids and the key dissolved metals for each site are summarized in Figure 7, while Figure 11 summarizes nutrients in the same way. Note that these median concentrations summarize all samples from all four wet weather events at each site to show longitudinal patterns within the catchment. Concentrations for the key pollutants of interest to ECan in this catchment (TSS, dissolved zinc and copper and ammonium) are then disaggregated and presented for each sampling time-point for each event per sampling site (Figures 8-10, 12) to highlight patterns within and between the wet weather events.

Christchurch City Council (CCC) have monitored instream water quality at the furthest downstream site (Riccarton Ave) sampled in this study (AVON09; Easting 2479427, Northing 5741438; near the brook's confluence with the Avon River/Ōtākaro) since 2008 on a monthly basis. Data from this monitoring programme are reported annually as a requirement of the Council's interim global stormwater consent (resource consent number CRC090292; Margetts and Marshall, 2016). CCC have also sampled during specific wet events in 2012 and 2014 as reported by Margetts (2013, 2014). These previous sampling data are used for comparison in the discussion below.

3.2.1. Total suspended solids (TSS)

Median concentrations of total suspended solids (TSS) generally exceeded the guideline value of 25 mg/L (Ryan, 1991; as used for this catchment by Margetts and Marshall (2016)) with the largest exceedance at Riccarton Ave (Figures 7). Although large amounts of TSS enter the Matipo stormwater ponds at the very top of the catchment, they are substantially reduced after passing through the ponds (pollutant removal within the Matipo ponds is discussed in detail in section 3.3). However, large amounts of TSS are subsequently conveyed to Addington Brook further down-stream of Deans Ave just before it converges with the Avon River/Ōtākaro (Figure 7). TSS concentrations are typically highest during the earlier sampling points at each site, reflecting the initial ('first') flush of solids from impervious surfaces following rainfall (Figure 8). Nonetheless, concentrations at the receding end of the storm events were still higher at Riccarton Ave (and to a lesser extent Deans Ave) by comparison to concentrations measured in previous wet weather events. For instance, TSS concentrations measured by the Christchurch City Council (CCC) during wet weather in 2012 and 2014 found values of 8 (Oct, 2012 – at recession of event), 13 (Nov, 2012 – at recession of event), 140 (March, 2014 – at peak of event) and 48 (May, 2014 – at recession of event) mg/L TSS (Margetts, 2013 and Margetts, 2014), which are much lower than concentrations

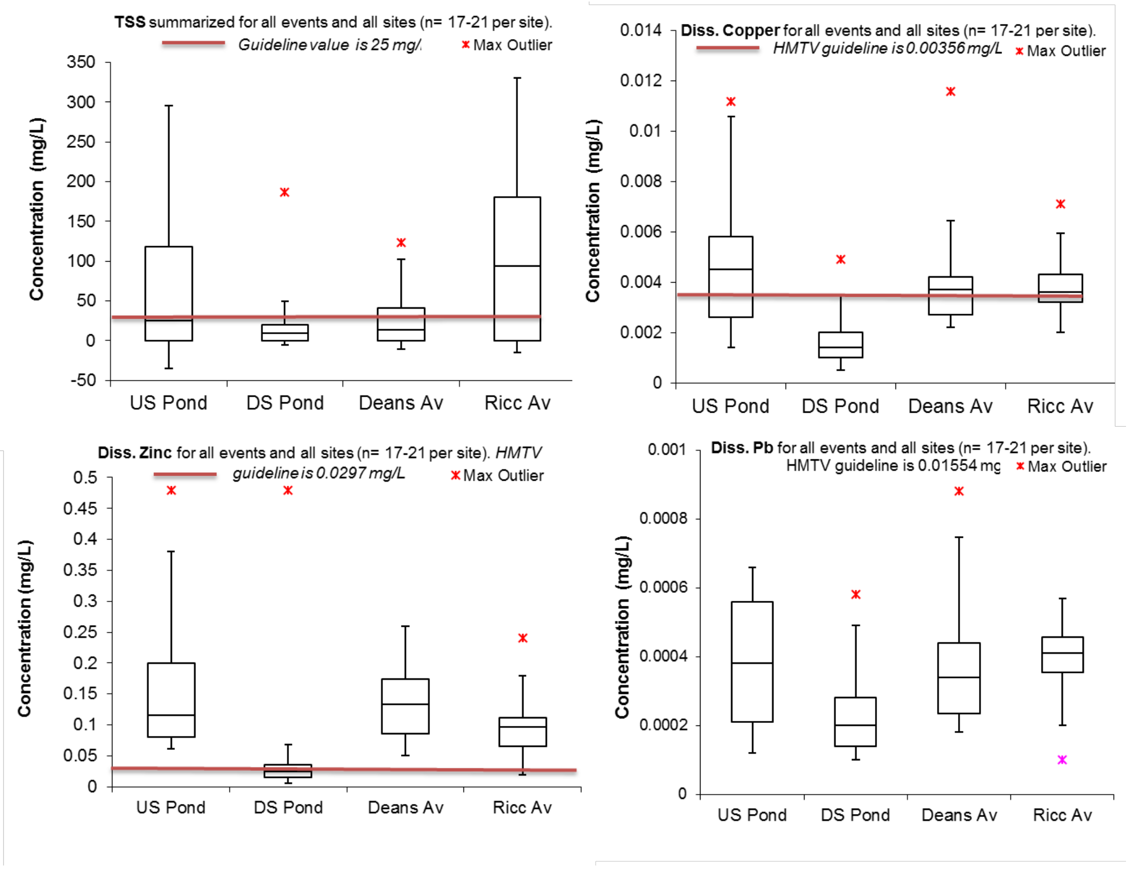


Figure 7. Summary Distribution of Total Suspended Solids (TSS) and dissolved metal (Zn, Cu and Pb) concentrations at each sampling site for all events (* denotes outliers ± 1.5x Inter Quartile Range (IQR); LWRP: Land and Water Regional Plan; HMTV: hardness modified trigger values (ANZECC 2000)).

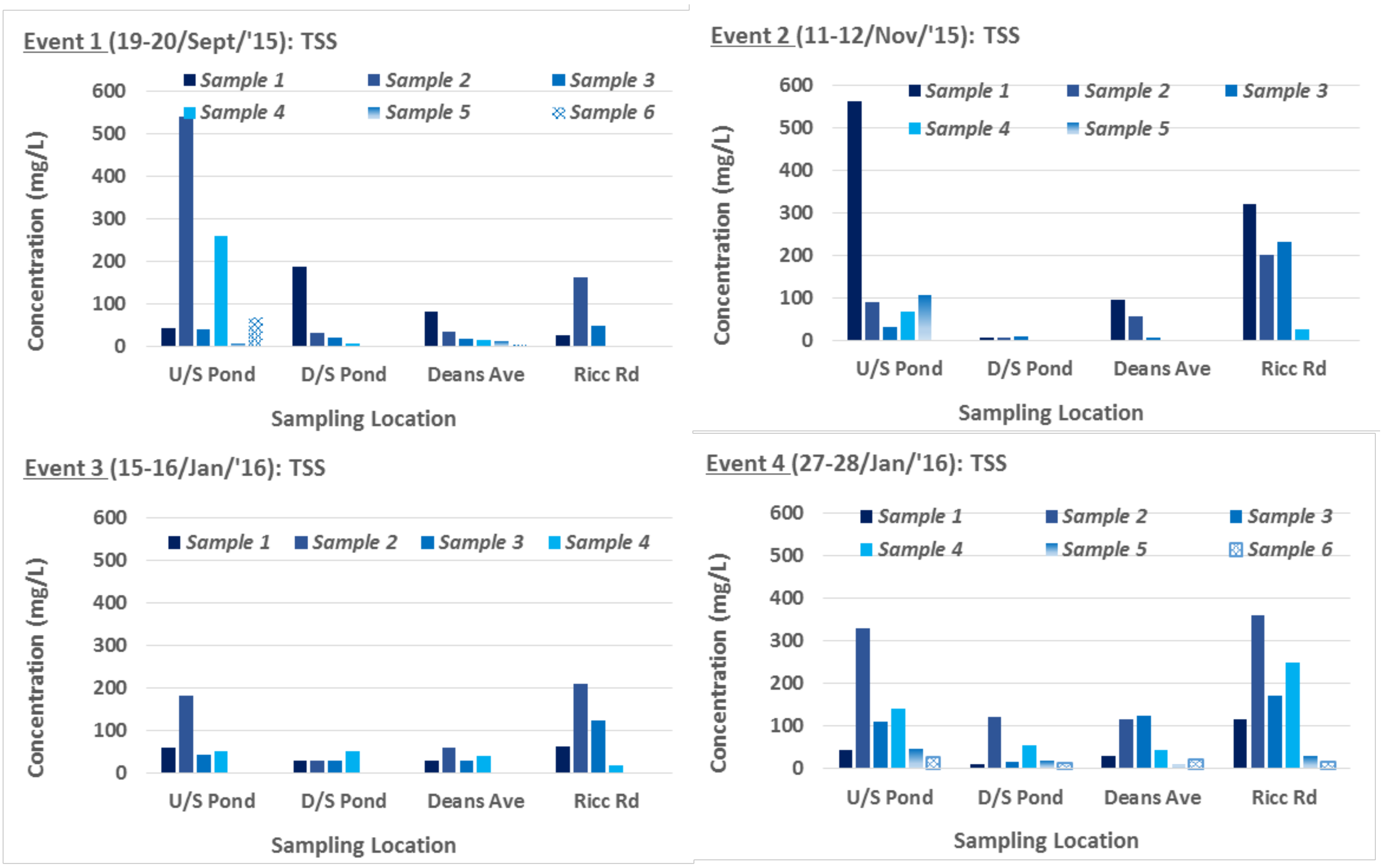


Figure 8. Total Suspended Solids (TSS) concentrations throughout each wet weather event for sampling sites.

measured in the 2015-2016 events (Figure 8). These trends in TSS concentrations between sampling sites are consistent across all four wet weather events but there are no clear patterns of concentrations to rainfall conditions since overall largest concentrations were seen in events 2 and 4, which are small and large events, respectively (Figure 8 and Table 1). Charters (2016) measured TSS concentrations between 200-450 mg/L in first-flush samples *directly* from impervious surfaces near this part of the catchment. Although samples did not represent in-stream mixed concentrations, they also highlight the large sediment load in stormwater runoff. There are significant stormwater pipes entering the brook near the netball courts of South Hagley Park and on the south side of Riccarton Ave, which convey substantial runoff during storm events, along with higher suspended solids loads. Therefore, it would be prudent to focus efforts on targeted sampling and pollutant mitigation at the main discharge points at this end of the brook to reduce the amount of solids entering the Avon River/Ōtākaro. It would also be beneficial to understand the amount of particulate metals at these points to enable co-treatment of TSS and particulate metals concurrently. It is possible that sediment may be entering the brook directly in the Hagley Park section where banks are steep and unstable in some reaches.

3.2.2. Dissolved Metals - Zinc (Zn), Copper (Cu) and lead (Pb)

Dissolved zinc (Zn) was consistently and highly elevated above the relevant LWRP (hardness-modified) in-stream trigger value (HMTV) guideline of 29.7 µg/L (0.0297 mg/L) throughout the catchment (Figure 7). In a similar pattern to TSS, large amounts of dissolved zinc enter the Matipo stormwater ponds at the very top of the catchment, but are substantially reduced after passing through the ponds (discussed in detail in section 3.3). However, concentrations substantially increase down-stream of these ponds where Deans Ave has the highest median (0.13 mg/L) concentration (and to a lesser extent Riccarton Ave at 0.097 mg/L) (Figure 7). The Deans Ave site captures the majority of runoff from the industrial/commercial sector within the Addington catchment and large galvanized roof areas in this sub-catchment have been shown to contribute very high concentrations of zinc, mainly in dissolved form, to stormwater runoff (Charters, 2016 and unpublished UC data from throughout 2016). Concentrations measured by the CCC during wet weather events at Riccarton Ave – 0.16 (Oct, 2012 – at recession of event), 0.15 (Nov, 2012 – at recession of event), 0.21 (March, 2014 – at peak of event) and 0.13 (May, 2014 – at recession of event) mg/L (Margetts, 2013 and Margetts, 2014), were comparable to those measured in the 2015-2016 events reported in this study of 0.019-0.240 mg/L (Figure 9). These data highlight that dissolved zinc has been a problematic pollutant in Addington Brook for some time. While dissolved Zn concentrations are typically highest during the earlier sampling points at each site, they remain moderately

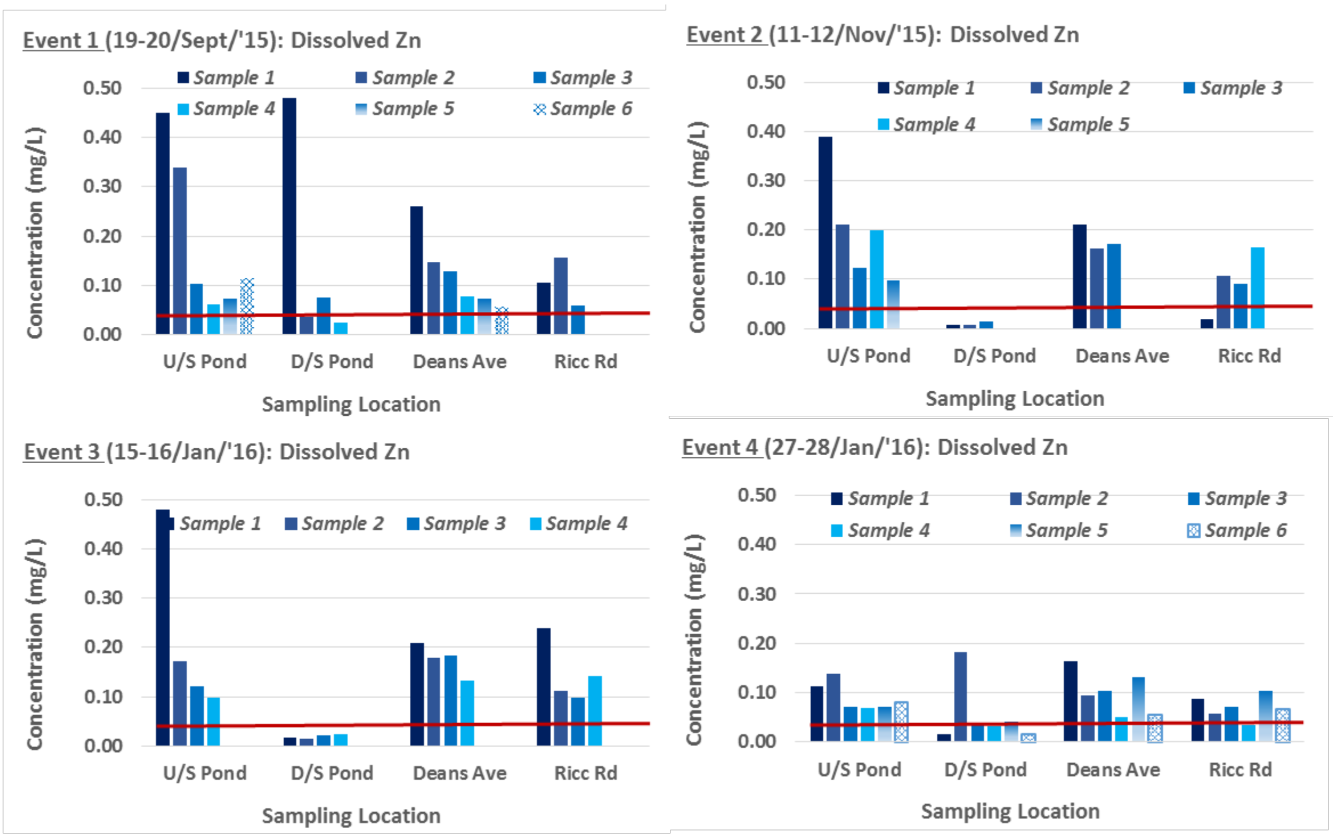


Figure 9. Dissolved Zinc (Zn) concentrations throughout each wet weather event for sampling sites.

elevated throughout the storm duration and do not clearly decline in the later samples (Figure 9). This may be explained by the fact that dissolved zinc concentrations are known to originate from galvanized roofs and downpipes so as long as rain is in contact with these surfaces, zinc will dissolve from the galvanized material (to various degrees depending on type and condition of galvanized surface) producing elevated dissolved zinc concentrations in stormwater runoff. Charters (2016) recently identified that disproportionally high loads of Zn in the Addington Brook are derived from roof runoff. Given the ubiquitous nature of dissolved zinc in Christchurch urban waterways, it would wise to implement source-control of this highly bioavailable metal, especially given dissolved fractions are much more difficult to remove than particulate fractions. While TSS concentrations are of most concern for the Riccarton Ave location, it appears that dissolved Zn should be targeted further up-stream at the Deans Ave location where its concentration is consistently highest (Figure 7).

Dissolved copper concentrations mainly exceeded the recommended LWRP (hardness-modified) in-stream guideline value of 3.56 µg/L (0.00356 mg/L) in the US Pond at the top of the catchment but concentrations in the pond's outflow were well below this (Figure 7). In a consistent pattern of increasing pollutant concentrations down-stream, as seen for TSS and dissolved Zn, dissolved copper concentrations substantially increased at Deans Ave and Riccarton Ave although median concentrations for both sites were only 0.004 mg/L and barely above the HMTV guideline value (Figure 7). Concentrations measured by the CCC during wet weather events at Riccarton Ave in the preceding years sampling were similar; 0.0033 (Oct, 2012 – at recession of event), 0.0027 (Nov, 2012 – at recession of event), 0.018 (March, 2014 – at peak of event) and 0.003 (May, 2014 – at recession of event) mg/L (Margetts, 2013 and Margetts, 2014), to those measured in the 2015-2016 events reported in this study of between 0.002-0.007 mg/L (Figure 10). These data indicate that copper is removed in the Matipo ponds and is not a major concern in mixed in-stream water downstream in Addington Brook. However, it should be noted that highly elevated copper concentrations have been measured in mixed surface waters when runoff from copper roofs (and corroded air-conditioning pipes) discharge to it (e.g. O'Sullivan *et al*., 2012) although it is reported that no copper roofs exist within the Addington catchment Charters (2016).

Dissolved lead (Pb) did not exceed the guideline value stipulated for this 'Spring fed – Urban' waterway and concentrations for all sampling locations and wet weather events were < 0.001 mg/L, which is comparable to previous wet weather events (<0.0015 mg/L) reported by Margetts (2013) and Margetts (2014). Lead is therefore not discussed further as it does not appear to be a pollutant of concern.

3.2.3. Nutrients

Total nitrogen (TN) and total phosphorus (TP) concentrations measured throughout each event are summarized for each location (Figure 11). Concentrations of TP and TN between sampling locations are generally similar, although in a consistent pattern seen within the catchment for other key pollutants, nutrients are retained within the Matipo pond system with concentrations then increasing down-stream of its outflow from other landuse activities. Concentrations of TN measured by the CCC during wet weather events in Addington Brook in the preceding years were similar; 0.95 (Oct, 2012 – at recession of event), 1.2 (Nov, 2012 – at recession of event), 1.6 (March, 2014 – at peak of event) and 1.5 (May, 2014 – at recession of event) mg/L (Margetts, 2013 and Margetts, 2014), compared with the 2015-2016 events reported in this study of between 1.14-1.70 mg/L (Figure 11). Similarly, concentrations of TP measured by the CCC during wet weather events in Addington Brook in the preceding years were comparable; 0.079 (Oct, 2012 – at recession of event), 0.1 (Nov, 2012 – at recession of event), 0.56 (March, 2014 – at peak of event) and 0.28 (May, 2014 – at recession of event) mg/L (Margetts, 2013 and Margetts, 2014), to those measured in the 2015-2016 events of between 0.08-0.90 mg/L (Figure 11).

A phosphorus source within the catchment could include surfactants conveyed in runoff during wash-down of vehicles (i.e. on impervious hardstand areas). Elevated phosphorus (especially Dissolved Reactive Phosphorus (DRP)) concentrations could lead to eutrophication, with excess algal growth and potential algal blooms especially in slow moving waters.

Ammonium – nitrogen (NH_4^--N) is a pollutant of potential concern in the catchment (pers. comm. Michele Stevenson, ECan). Concentrations in previous wet weather events reported in Addington Brook were 0.1 (Oct, 2012 – at recession of event), 0.16 (Nov, 2012 – at recession of event), 0.120 (March, 2014 – at peak of event) and 0.23 (May, 2014 – at recession of event) mg/L NH_4¯N (Margetts, 2013 and Margetts, 2014). These concentrations are below the maximum NH_4¯N guideline concentration of 1 mg/L stipulated to prevent toxicity to freshwater fish (ANZECC, 2000). In the 2015-2016 wet weather events (Figure 12), the median NH_4¯N concentration across all events and sites was 0.19 mg/ L (min: 0.01- max: 0.81 mg/L), which are also all below the recommended ANZECC guideline. It is interesting to note that generally higher NH_4¯N concentrations were measured during the smallest rainfall event (event 2) and concentrations become diluted during larger storm events. Dry weather ammonium at high concentrations could come from a number of potential sources, including resident birds, industrial point discharges, and others.

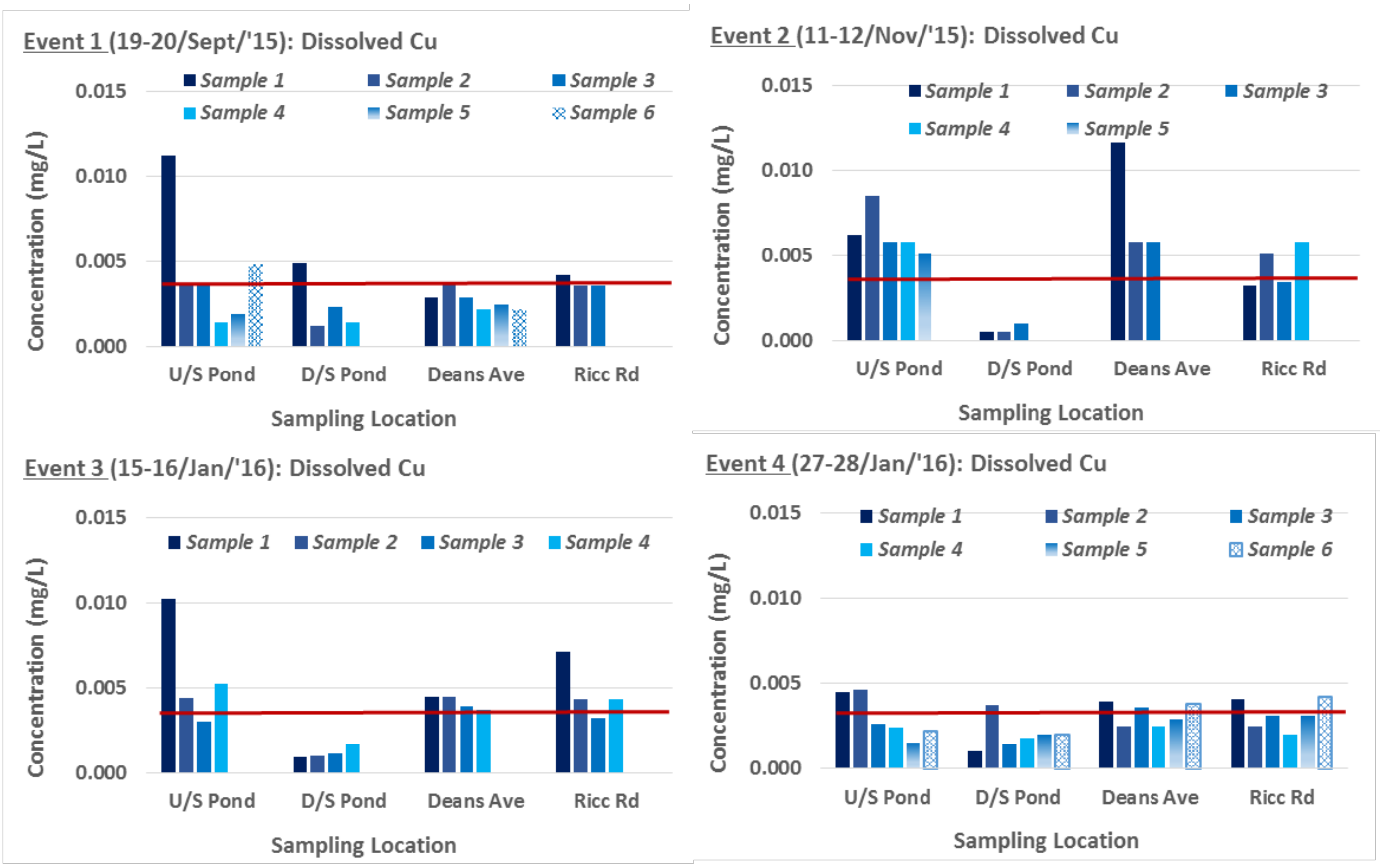
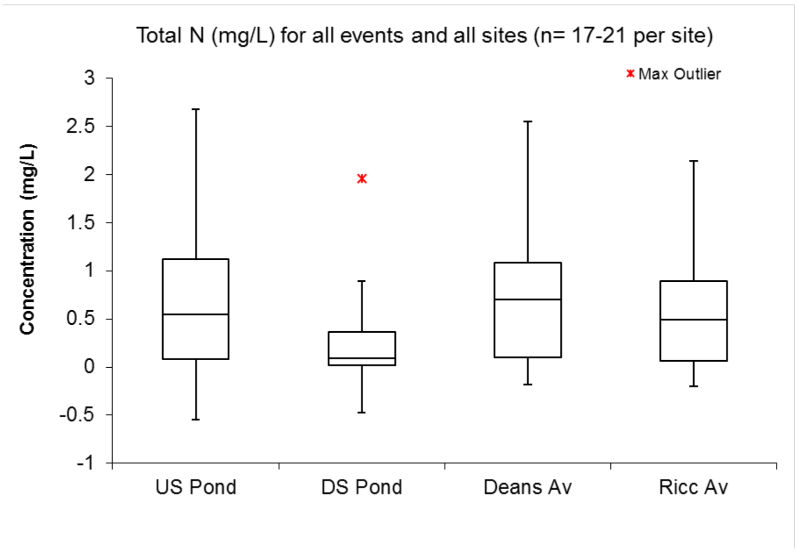


Figure 10. Dissolved Copper (Cu) concentrations throughout each wet weather event for sampling sites.



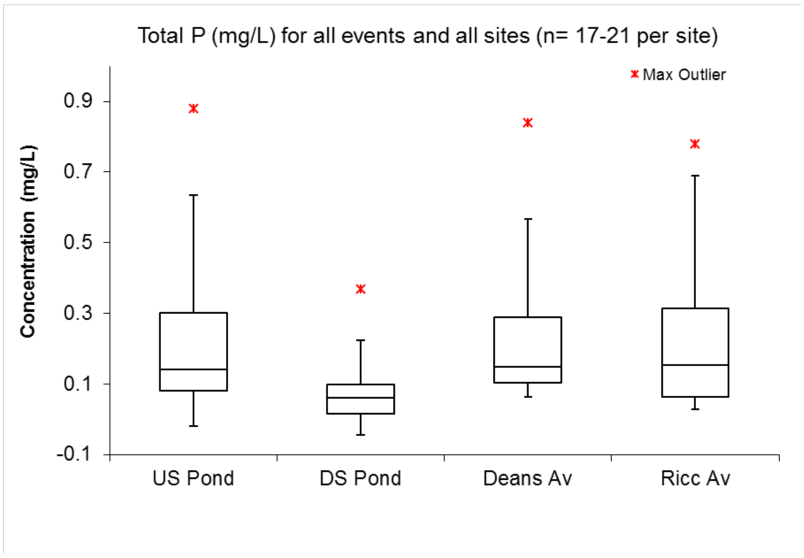


Figure 11. Summary distribution of total phosphorus and total nitrogen concentrations at each sampling site (* denotes outliers ± 1.5x Inter Quartile Range (IQR); for all sites for all events.

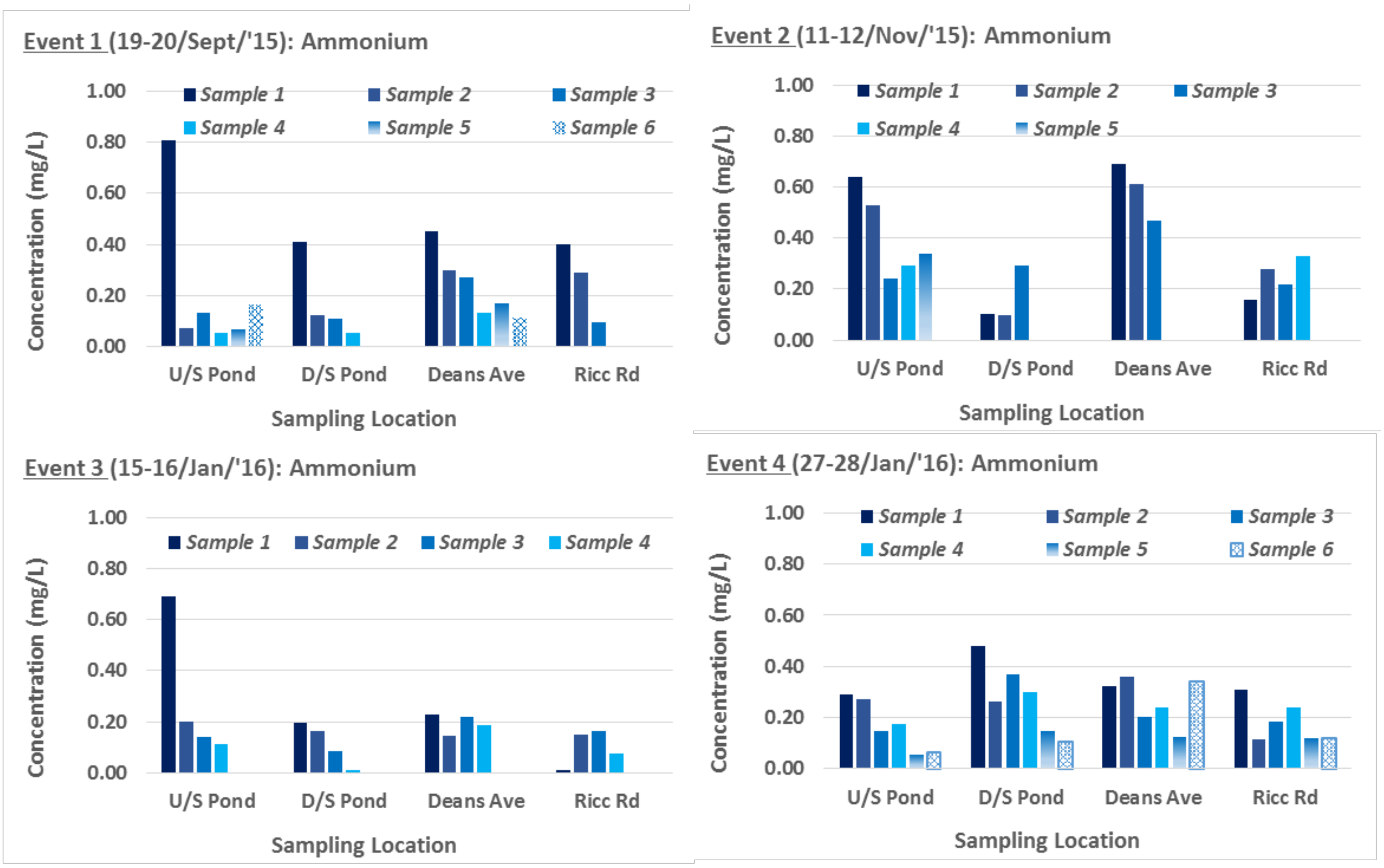


Figure 12. Ammonium (NH_4) - N concentrations throughout each wet weather event for sampling sites.

3.3. Pollutant retention by the Matipo Ponds System

The overall performance of the Matipo stormwater pond system to treat pollutants was assessed in detail by examining the speciation of nutrients, metals and solids between the inflow and outflow during each sampling event. Figures 13 (phosphorus, P), 14 (nitrogen, N), 15 (TSS) and 16-17 (metals) present these data. Table 2a summarizes the concentrations and removal efficiencies for these pollutants in 2015-2016 and similarly, Table 2b summarizes the pond's performance as reported in 2009 by EOS Ecology. Table 3 highlights the significance of the differences between the inflow and outflow concentrations for these pollutants in 2015-2016 (sampling time-points for rainfall, water level and concurrent pollutant concentrations are provided in Appendix A).

Table 3. Statistical results of pollutants in the inflow and outflow of the Matipo ponds (using a paired, 2-tailed t-test) with a probability (p) values of significance asterix-tagged depending on strength of significance; ***p<0.001; **p<0.01 and *p<0.05, n= 17 n/s = not significant.

Pollutant name	Pollutant code	p value	Strength of Significance
Total Phosphorus	TP	0.031	*
Dissolved Reactive Phosphorus	DRP	0.048	*
Total Nitrogen	TN	0.028	*
Total Kjeldahl Nitrogen	TKN	0.145	n/s
Ammonium - N	NH_4	0.507	n/s
Nitrate + Nitrite	NO_3/NO_2	0.967	n/s
Total Suspended Solids	TSS	0.010	**
Turbidity	Turbidity	0.003	***
Dissolved Zinc	Zn -dissolved	0.025	*
Dissolved Copper	Cu - dissolved	0.0001	***

3.3.1. Nutrient (Phosphorus and Nitrogen species) and Solids

Total nitrogen (TN) is the sum of the organic fractions including total kjeldahl nitrogen (TKN) and ammonium (NH_4), as well as inorganic nitrate and nitrite (NO_3/NO_2). TN in the stormwater ponds was comprised mostly of TKN as seen by the speciation concentrations (Figure 13). While water discharging from the detention component of the pond system (i.e. outflow) was usually much lower in total N concentration compared to the inflow and significantly so (Table 3), the inorganic nitrate/nitrate concentrations were sometimes higher than their inflow values (Figure 13). This occurred when the rainfall durations and depths were larger (events 1 and 4; see Table 1) and suggests that nitrogen in the pond was converted from organic to inorganic fractions through the processes of mineralization (TKN to NH_4) and subsequent nitrification (NH_4 to NO_3) in the larger rainfall events. Additionally, TN and nitrate removal efficiencies between the earlier 2008 winter sampling events and

Table 2a. *Median* inflow (In) and outflow (Out) concentrations (mg/L) and removal efficiencies (%Δ) of the KiwiRail Stormwater Ponds (Matipo Street) system **2015-2016** along with key rainfall metrics at the time of sampling, n = 17. – means net pollutant export from the system.

	2015-2016 (Spring-Summer)														
Event (start)	**18/09/'15**			**11/11/'15**			**15/01/'16**			**27/01/'16**			**Overall**		
Rainfall intensity (mm/hr)	*0.80*			*0.51*			*0.89*			*0.93*			*0.85*		
Rainfall depth (mm)	*30.67*			*9.40*			*12.20*			*28.30*			*28.3*		
Event duration (hrs)	*38.50*			*18.50*			*13.75*			*32.00*			*25.25*		
Pollutant (g/m^3)	**In**	**Out**	**%Δ**	**In**	**Out**	**%Δ**	**In**	**Out**	**%Δ**	**In**	**Out**	**%Δ**	**In**	**Out**	**%Δ**
TSS	165	26	84	88	6	71	55	30	54	78	17	67	83.00	21.25	**69**
Diss.Zn	0.11	0.06	49	0.21	0.01	96	0.15	0.02	87	0.08	0.02	74	0.13	0.02	**80**
Diss.Cu	0.0036	0.0019	49	0.0062	0.0005	92	0.0048	0.0011	78	0.0025	0.0019	24	0.0042	0.0015	**63**
Diss.Pb	0.0002	0.0001	38	0.0002	0.0001	33	0.0005	0.0002	71	0.0004	0.0003	29	0.0003	0.0002	**36**
TN	1.41	1.07	24	1.97	0.61	69	1.29	1.18	9	1.41	0.96	32	1.41	1.01	**28**
TKN	1.08	0.70	35	1.62	0.43	73	1.01	1.07	-6	0.82	1.07	-30	1.04	0.88	**15**
NH_4	0.10	0.12	-15	0.53	0.10	81	0.17	0.13	27	0.16	0.28	-75	0.17	0.12	**6**
NO_3/NO_2	0.12	0.25	-100	0.35	0.19	47	0.28	0.11	60	0.13	0.18	-35	0.21	0.18	**6**
TP	0.61	0.14	76	0.34	0.14	60	0.26	0.19	29	0.18	0.22	-21	0.30	0.16	**44**
DRP	0.08	0.01	91	0.15	0.01	90	0.10	0.05	47	0.06	0.06	0	0.09	0.03	**69**

Table 2b. Median inflow (In) and outflow (Out) concentrations (mg/L) and removal efficiencies (%Δ) of the KiwiRail Stormwater Ponds (Matipo Street) system in **2008** (EOS Ecology, 2009) along with key rainfall metrics at the time of sampling, n = 22-24. – means net pollutant export from the system.

	2008 (Winter)														
Event (start)	**02/06/'08**			**17/06/'08**			**27/06/'08**			**23/07/'08**			**Overall**		
Rainfall intensity (mm/hr)															
Rainfall depth (mm)	2.6			0.6			11.6			35.8			12.65		
Event duration (hrs)	11.99			20.15			25.02			94.16			37.83		
Pollutant (g/m^3)	**In**	**Out**	**%Δ**	**In**	**Out**	**%Δ**	**In**	**Out**	**%Δ**	**In**	**Out**	**%Δ**	**In**	**Out**	**%Δ**
TSS	140	7.4	94.7	110	7	93.6	61	45.5	25.4	67	51	23.9	94.5	27.73	**71**
Diss.Zn	1.2	0.1	91.7	0.805	0.10	87.6	0.375	0.235	37.3	0.31	0.18	41.9	0.673	0.154	**77**
Diss.Cu	0.0565	0.0029	95.0	0.0365	0.0032	91.4	0.018	0.01	44.4	0.013	0.0079	39.6	0.0331	0.0059	**81**
Diss.Pb	0.0195	0.00079	96.0	0.0345	0.0012	96.5	0.013	0.0087	33.1	0.012	0.0079	34.2	0.0198	0.0047	**77**
TN	3.55	1.0	71.8	8.3	1.65	80.1	1.8	1.5	16.7	1.1	1.0	9.1	3.688	1.288	**65**
TKN	2.5	0.77	69.2	7.75	1.3	83.2	1.4	1.3	7.1	0.995	0.850	14.60	3.161	1.055	**67**
NO_3/NO_2	0.995	0.225	77.4	0.56	0.31	44.6	0.195	0.23	17.9	0.0775	0.115	-48.4	0.457	0.22	**52**

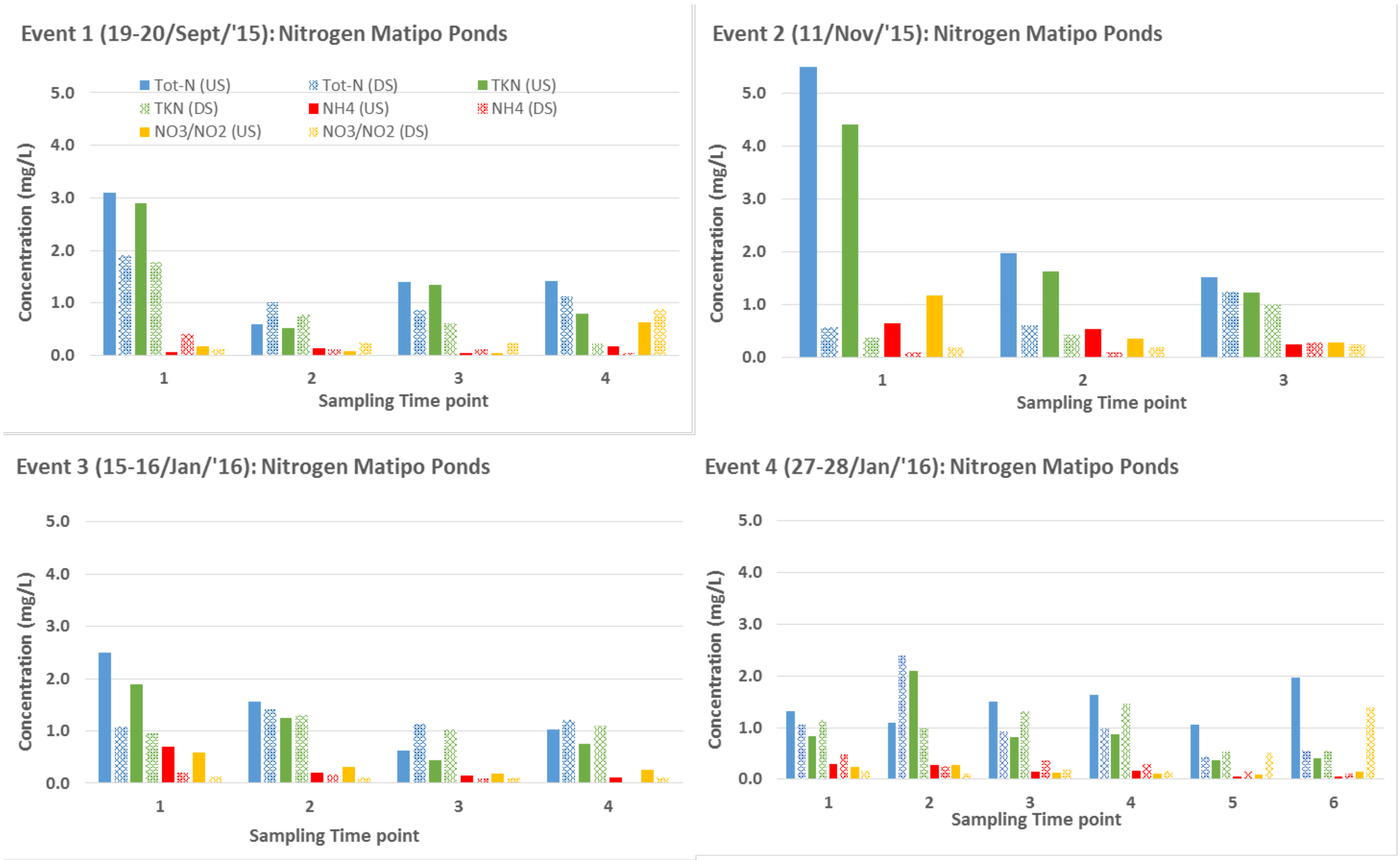


Figure 13. Nitrogen species in the Matipo Ponds inflow (US; Up-Stream pond) and outflow (DS; Down-Stream pond).

the 2015-2016 spring-summer sampling events seems to be poorer in the later years although it would be important to re-sample during the same seasons for definite comparisons (Tables 2a and 2b). Elevated nitrate/nitrite concentrations can be a concern given their high solubility and contribution to eutrophic algal growth. Although the LWRP does not have a guideline value for NO_3-N, the ANZECC (2000) water quality guidelines stipulate a trigger value of 0.444 mg/L for lowland rivers to avoid excessive algal growth. Median concentrations in the pond inflow (US Pond) and outflow (DS Pond) in this study were 0.230 (0.05-1.17) mg/L and 0.18 (0.10-1.40) mg/L, respectively (Figures 6 and 13).

Total phosphorus (TP) is the sum of the particulate and dissolved (DRP) fractions, with the majority of phosphorus in the stormwater ponds comprised of particulate fractions as seen by the speciation concentrations (Figure 14). Despite the ability of the ponds to substantially and significantly (e.g. $p<0.05$) reduce net phosphorus overall, DRP concentrations consistently exceeded the LWRP guideline concentration of 0.016 mg/L in both inflow (median 0.08 (0.04-0.62) mg/L) and outflow (median 0.04 (0.01-0.10) mg/L) (Figure 7). During the most intense rainfall event sampled (#4; 0.93 mm/hr), TP and DRP concentrations were initially lower in the outflow compared with inflow stormwater but by the third sampling time-point, this pattern reversed, which was not observed in other events (Figure 14). The relationship between solids and TP was investigated to ascertain concurrent phosphorus removal as solids are settled from stormwater. However, only 34% of the data can be explained by their relationship (Appendix B), which suggests that targeting solids removal will not be very effective at removing most of the phosphorus concurrently.

Although solids (measured both as TSS and turbidity) concentrations were often very high in the stormwater inflow, the ponds were quite effective (significance $p<0.01$; Table 2a) at reducing these concentrations in the outflow, even during the largest events 1 and 4 (Figures 8 and 15). This is most likely attributed to adequate settling potential within the ponds despite the suspected hydraulic short-circuiting mentioned earlier.

3.3.2. Dissolved metal (zinc, copper, lead) concentrations

The data (Tables 2a and 2b; Figures 16 and 17) clearly show that the Matipo ponds system is still very effective at retaining dissolved metals since concentrations in the down-stream pond outflow (DS) are significantly (Table 3) much lower than in the up-stream pond first flush inflow (US). Furthermore, concentrations of all dissolved metals are almost consistently below their LWRP guideline values in the pond outflow, irrespective of sampling time point, with the exception of twice during event 1 and once in event 4 for zinc and copper (Figures 16 and 17). There was no consistent pattern in inflow metal concentrations as a function of rainfall parameters since longer duration or higher intensity events (Table 1) did not produce greatest metal runoff levels.

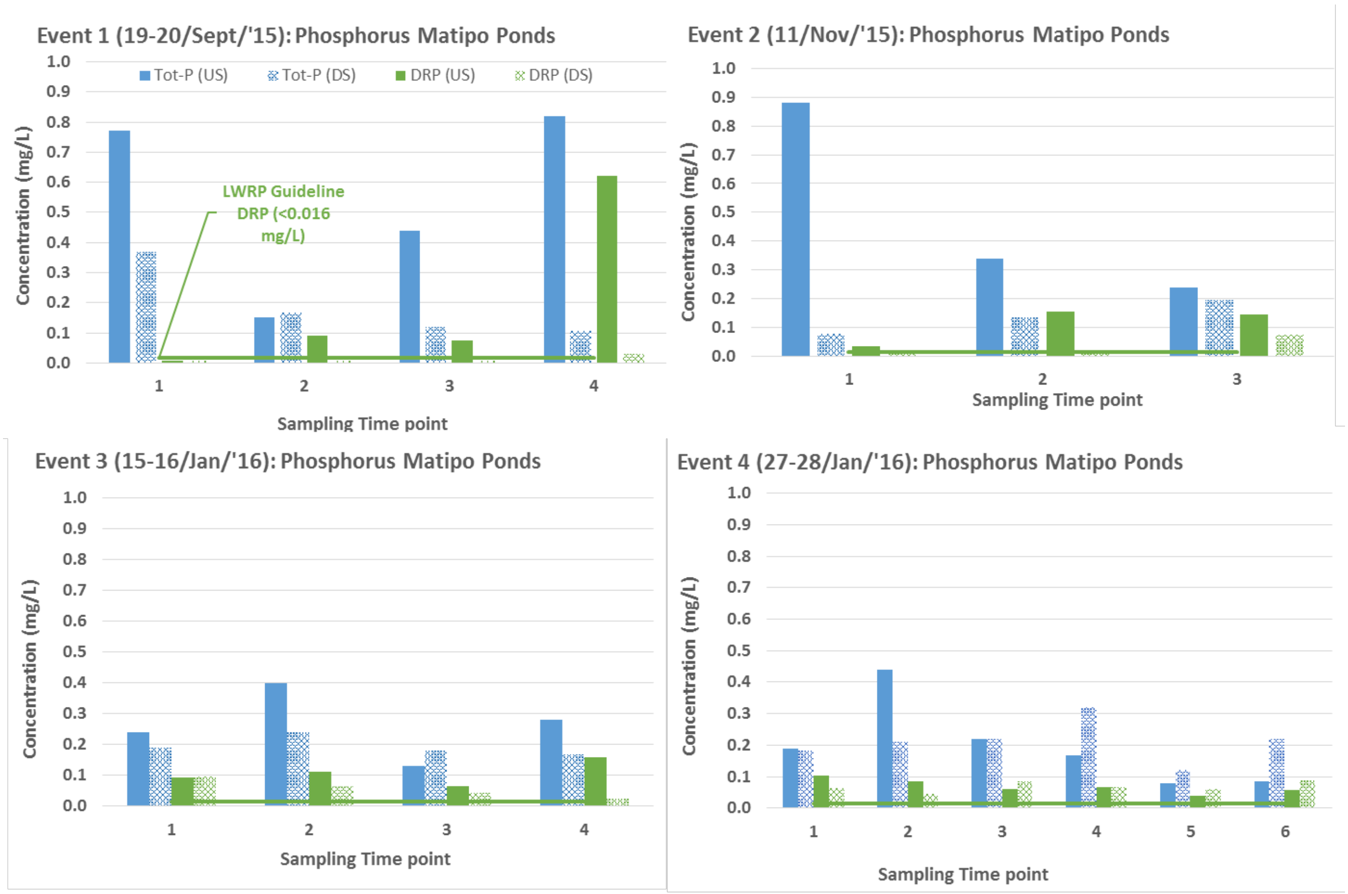


Figure 14. Phosphorus species in the Matipo Ponds inflow (US; Up-Stream pond) and outflow (DS; Down-Stream pond).

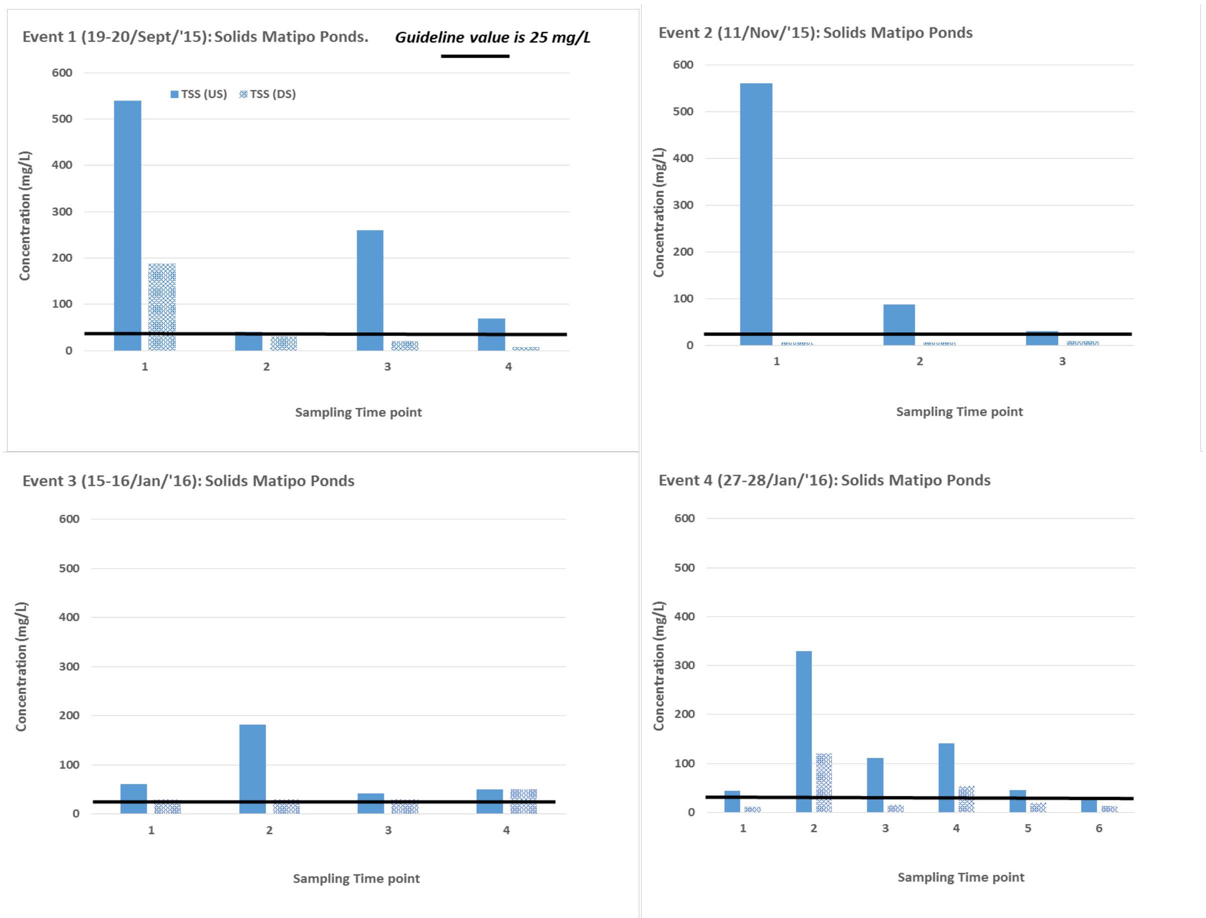


Figure 15. Solids in the Matipo Ponds inflow (US; Up-Stream pond) and outflow (DS; Down-Stream pond).

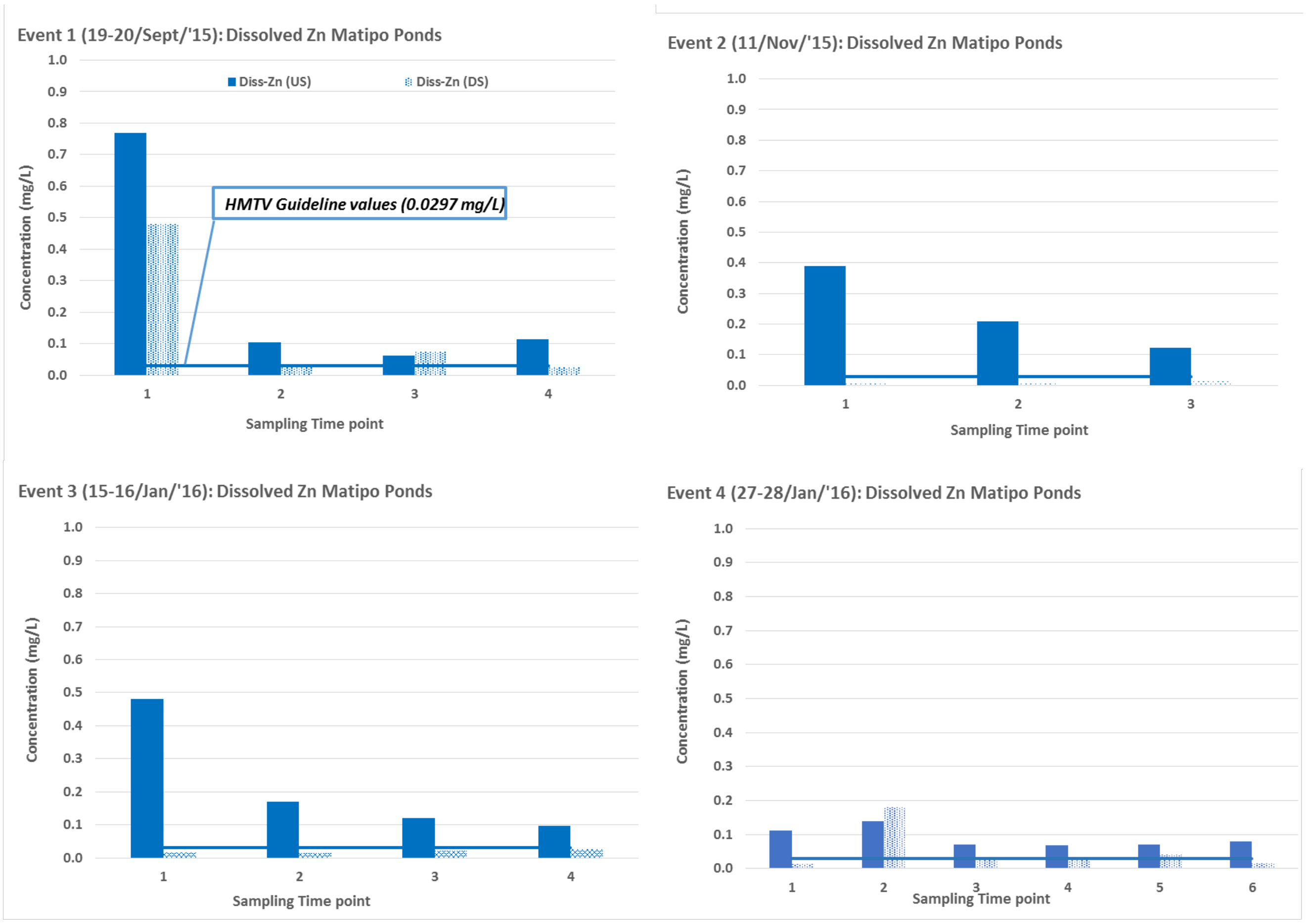


Figure 16. Dissolved zinc in the Matipo Ponds inflow (US; Up-Stream pond) and outflow (DS; Down-Stream pond).

Figure 17. Dissolved copper and lead in the Matipo Ponds inflow (US; Up-Stream pond) and outflow (DS; Down-Stream pond).

3.4. Pollutant Loads – Downstream Riccarton Ave Sampling Location

Flow at Riccarton Ave (Figure 3) was monitored concurrent to the time samples were collected for water quality, so pollutant loads for this site for the four wet weather sampling events were derived by multiplying the flow recorded by the concentration for the same time-point. The data were then expressed as statistically (median, minimum and maximum) summarised rate loads (g or mg)/min and are represented along with the flow for each event (Table 4). As mentioned earlier in section 2, the data show that surface water was sampled throughout the rain event at all characteristic time points (with the exception of event 1 at Riccarton Ave where the peak of the event was not captured), providing valuable information about the range of concentrations measured throughout each event at each location so that their pollutant loads could be estimated (Figures 18-23).

Overall, median pollutant loads are not clearly influenced by rainfall in the catchment (Table 4). Since these loads are a factor of in-stream mixed concentration and flow rate, and there were no consistent patterns in pollutant concentrations as a function of rainfall metrics as discussed earlier, it follows that higher pollutant loads are not necessarily observed in response to greater rainfall. However, event 4 which was the largest rainfall event, did yield largest net pollutant maximum loads (Table 4) compared to the earlier, smaller events.

For these four monitored events, with a median rainfall intensity of 0.78 mm/hr and a median depth of 23.35 mm, the Riccarton Ave location transports median loads of 1.808 *k*g/min TSS, 1.75 g/min dissolved zinc, 6.3 *m*g/min dissolved Cu and 7.1 *m*g/min of dissolved lead as well as 37.23 g/min TN and 8.25 g/min TP downstream into the Avon River/Ōtākaro (Table 4 and Figures 18-23). Since related water quality sampling found that most (on average 95%) of the zinc in this catchment is in the dissolved form (Charters, 2016), it may be extrapolated that the total zinc loads are similar to the dissolved zinc loads reported here (Figure 19). Since the data in this report represent in-stream mixed concentrations only and water was not sampled directly from pipe discharges, it is impossible to distinguish between what flowed into the stream during the rainfall events and what may represent some existing (stored) pollutants that may become mobilized when it rains. Sampling from key stormwater pipe discharges and mixed in-stream water at the same time, would enable an understanding of the mixing (and dilution) potential of the receiving waterway. Additionally, with flow and concurrent water quality data monitored at other sites in the catchment, it would be possible to compare pollutant loads at the different sub-catchment locations to estimate the greatest pollutant loads to the river system.

Table 4. In-stream mixed pollutant loads (mass/min) for Riccarton Ave for each sampling event (n=3-6 per event) along with summary rainfall metrics.

Event	**18-20/09/'15**			**11-12/11/'15**			**15-16/01/'16**			**27-28/01/'16**			**Average all events**		
Average Rainfall intensity (mm/hr)	0.80			0.51			0.89			0.93			0.78		
Rainfall depth (mm)	*30.67*			*18.50*			*13.75*			*30.50*			23.35		
Event duration (hrs)	*38.50*			*9.40*			*12.20*			*28.30*			22.10		
Pollutant (g/min) *Pb (mg/min)	***Med.***	***Min.***	***Max.***	***Med.***	***Min.***	***Max.***	***Med.***	***Min.***	***Max.***	***Med.***	***Min.***	***Max.***	***Med.***	***Min.***	***Max.***
TSS	*174*	*105*	*1808*	*3839*	*190*	*5851*	*3036*	*49*	*6426*	*5207*	*53*	*25020*	***1808***	*49*	*25020*
Diss.Zn	*0.42*	0.21	1.75	*1.68*	0.21	2.29	*3.18*	0.41	4.16	*1.88*	0.23	5.18	**1.75**	0.21	5.18
Diss.Cu	*0.0017*	0.0013	0.040	*0.064*	0.036	0.104	*0.11*	0.012	0.137	*0.066*	0.015	0.226	**0.063**	0.012	0.226
***Diss. Pb**	*1.18*	0.84	3.24	*3.78*	1.13	9.41	*11.17*	1.30	17.59	*10.42*	1.52	53.04	**7.10**	0.84	53.04
Diss. As	*0.01*	0.01	0.01	*0.02*	0.01	0.03	*0.04*	0.01	0.10	*0.05*	0.01	0.20	**0.03**	0.01	0.20
TN	*8.44*	4.38	19.31	*46.18*	9.52	71.23	*36.76*	3.66	60.28	*37.69*	6.87	121.10	**37.23**	3.66	121.10
TKN	*4.86*	1.39	12.95	*35.91*	6.51	61.06	*28.74*	2.28	47.74	*30.79*	2.16	105.06	**29.76**	1.39	105.06
NH_4	*1.61*	0.33	3.24	*4.01*	1.78	5.70	*4.59*	0.21	6.95	*3.28*	0.42	24.02	**3.64**	0.21	24.02
NO_3/NO_2	*3.78*	2.99	6.47	*8.65*	3.00	11.84	*7.87*	1.38	12.55	*9.15*	4.71	18.41	**8.26**	1.38	18.41
TP	*0.59*	0.59	3.01	*12.11*	1.10	17.81	*6.07*	0.33	10.30	*10.43*	0.47	27.72	**8.25**	0.33	27.72
DRP	*0.09*	0.05	0.32	*0.47*	0.07	0.81	*0.55*	0.07	1.46	*1.26*	0.28	3.40	**0.51**	0.05	3.40

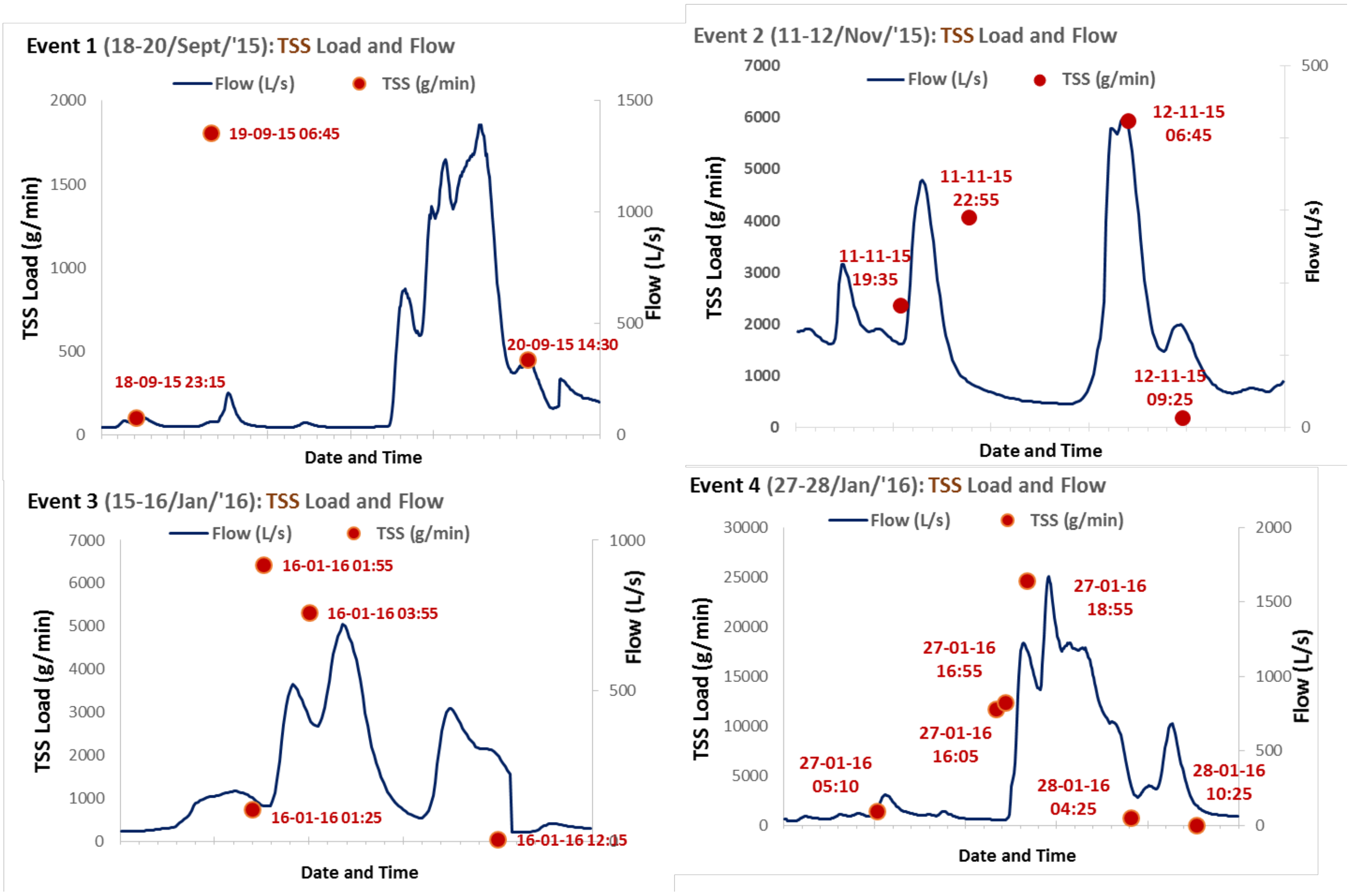


Figure 18. TSS loads, flow and sampling time-points at Riccarton Ave sampling location for all events in 2015-2016. Note different scales for y-axes.

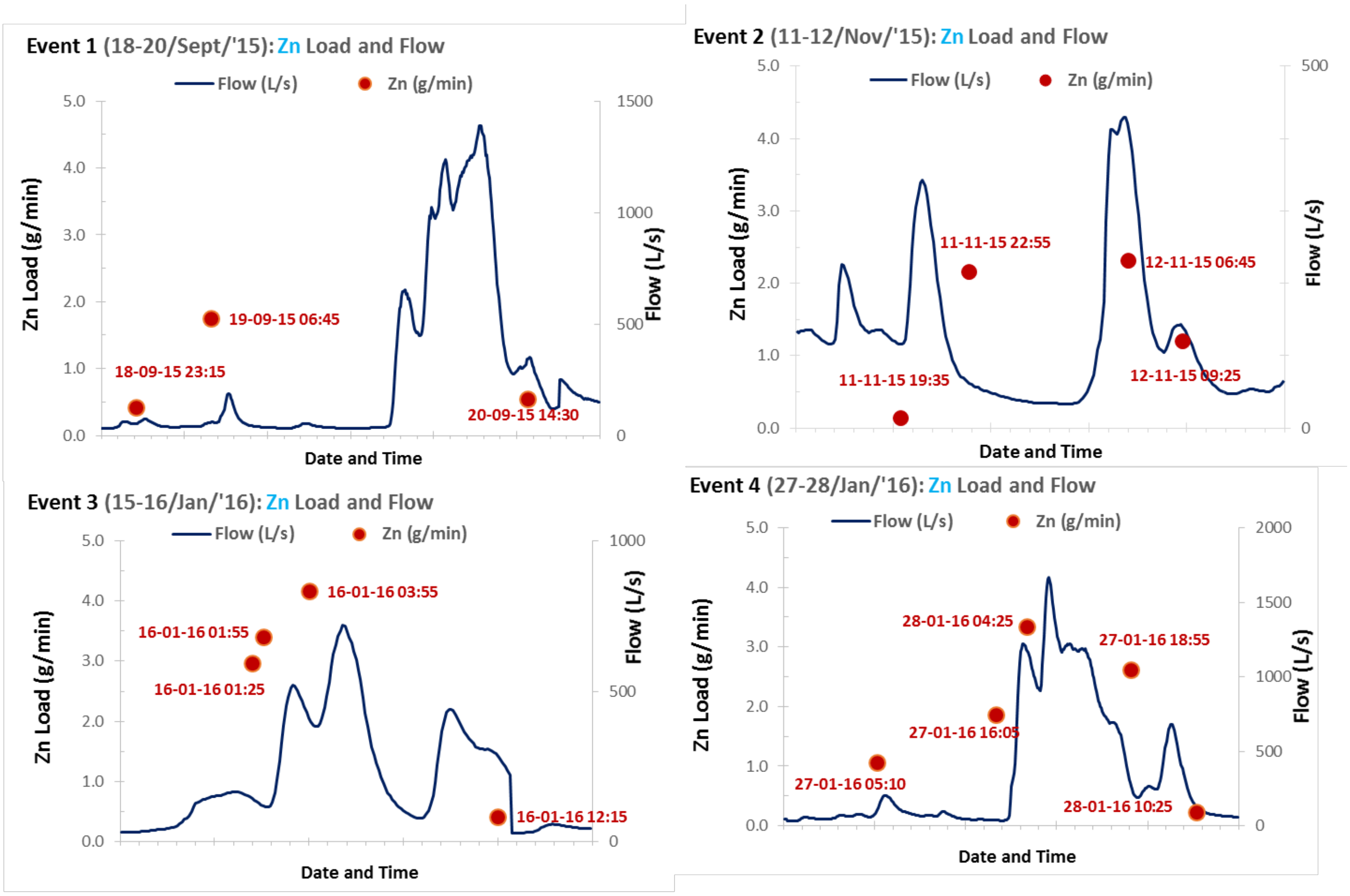


Figure 19. Dissolved Zn loads, flow and sampling time-points at Riccarton Ave sampling location for all events in 2015-2016.

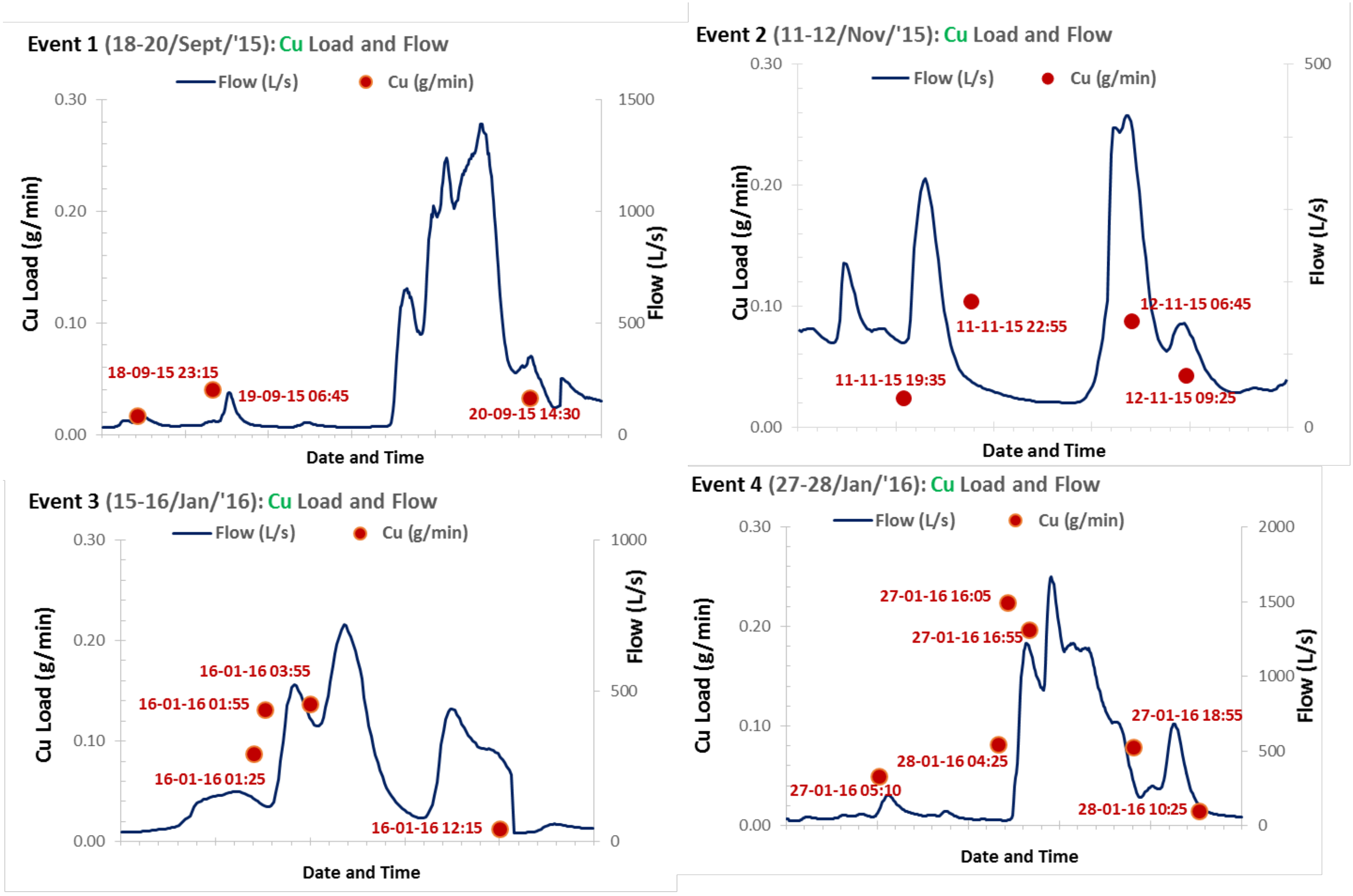


Figure 20. Dissolved Cu loads, flow and sampling time-points at Riccarton Ave sampling location for all events in 2015-2016.

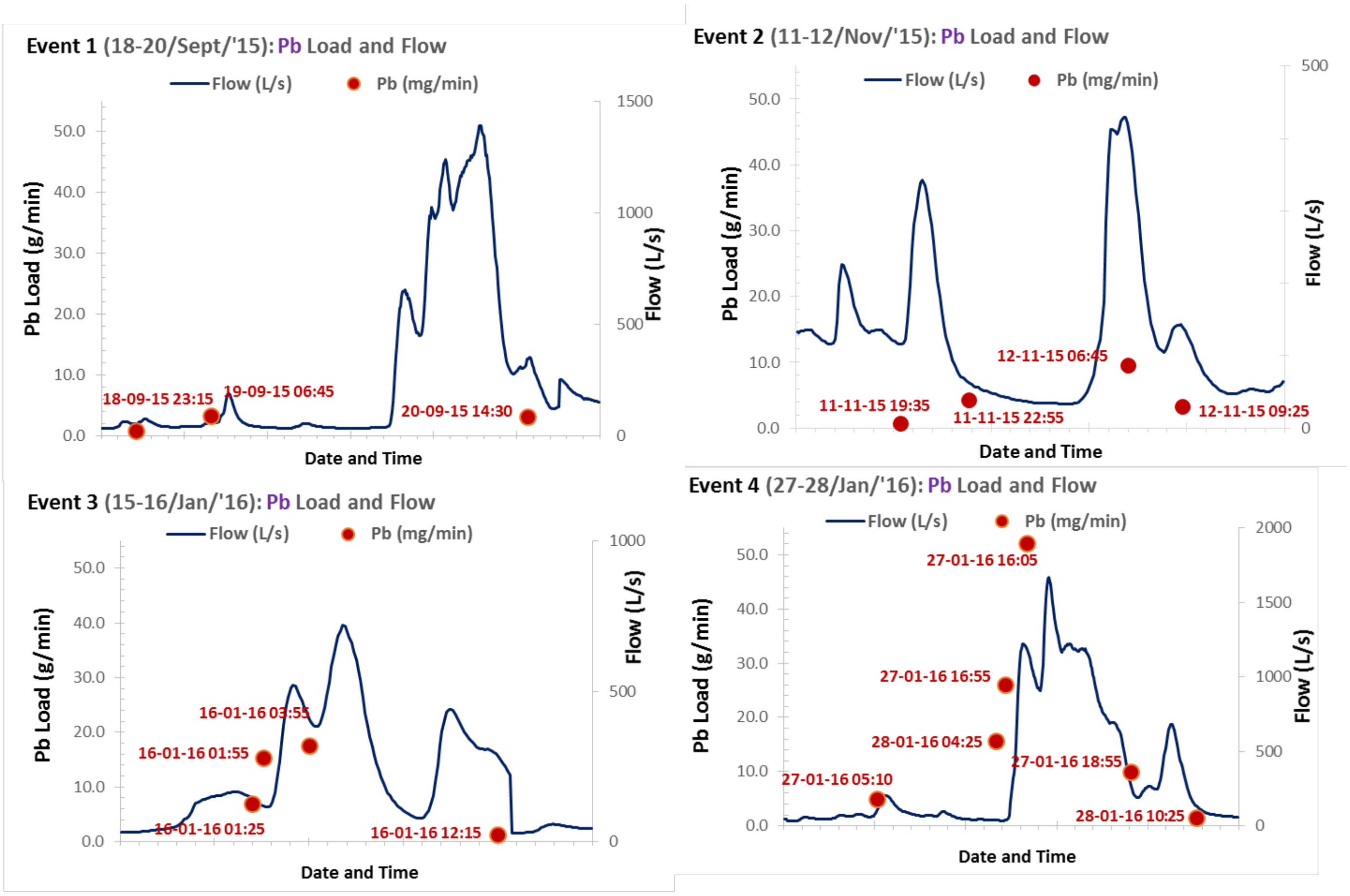


Figure 21. Dissolved Pb loads, flow and sampling time-points at Riccarton Ave sampling location for all events in 2015-2016.

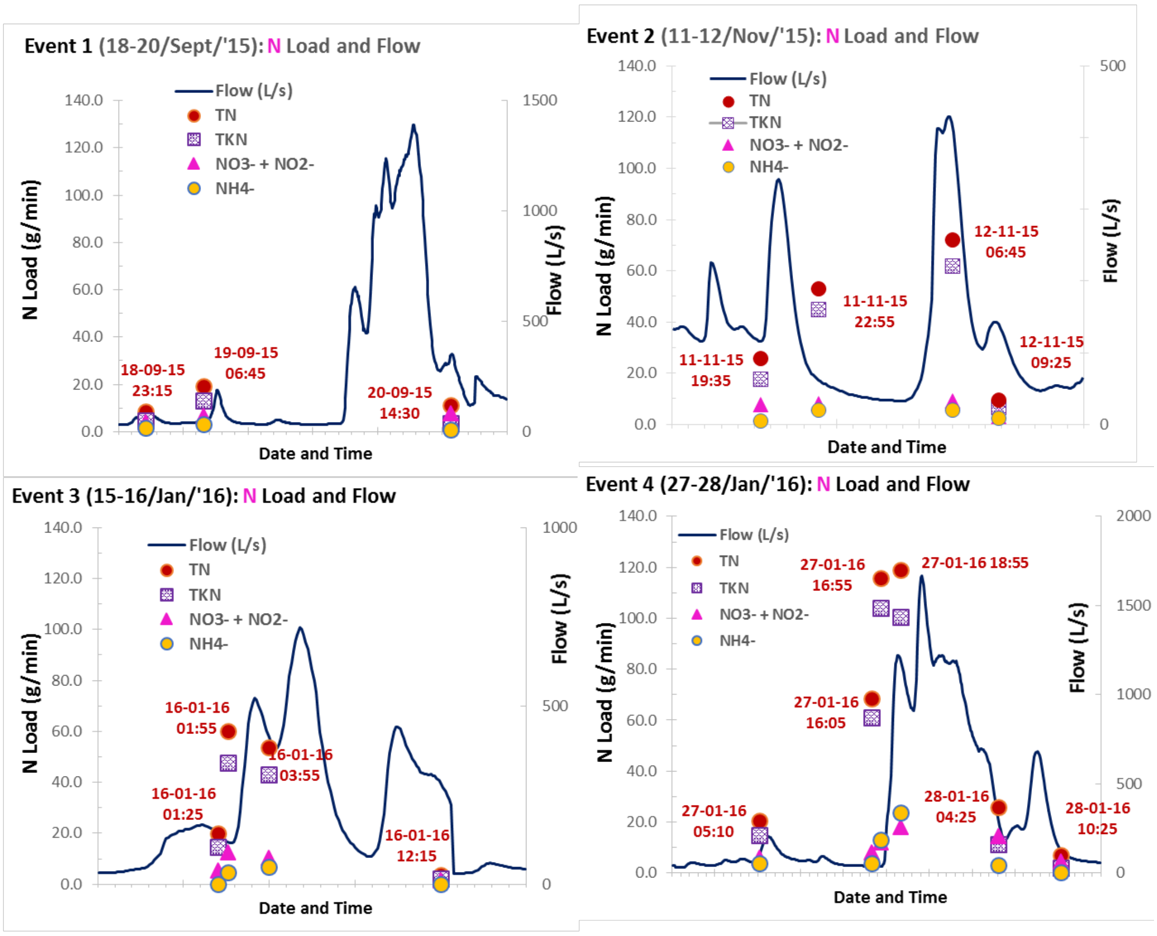


Figure 22. Nitrogen species loads, flow and sampling time-points at Riccarton Ave sampling location for all events in 2015-2016.

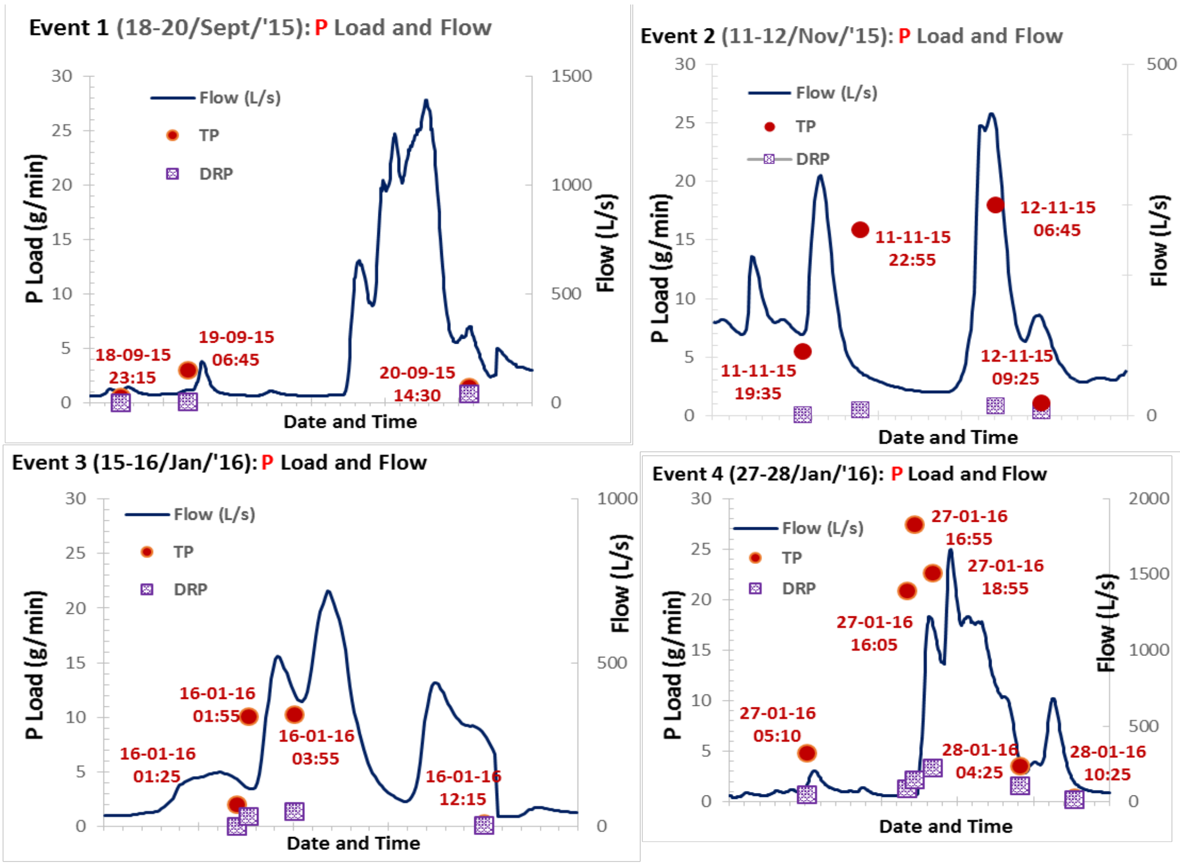


Figure 23. Phosphorus species loads, flow and sampling time-points at Riccarton Ave sampling location for all events in 2015-2016.

3.5. Pollutant Loads – Modelled versus measured at Riccarton Ave

The key stormwater metals of concern, dissolved zinc (Figure 19) and copper (Figure 20) loads, measured during four wet weather events for the Riccarton Ave sampling location were compared to dissolved zinc and copper loads predicted for all wet weather events by the MEDUSA model for the catchment (Table 5). MEDUSA delineated all impervious surfaces and generated metal loads for the roofs, carparks and roads (Charters, 2016). Modelled pollutant loads represent the dissolved metal load generated from those impervious areas for all (88) wet weather events in 2015, whereas the measured pollutant loads represent the in-stream dissolved metal loads for four wet weather events in 2015-2016.

Table 5. Modelled and measured dissolved pollutant loads at the Riccarton Ave sampling location (2015-2016). Data are presented as median dissolved metal load per event (**g/event**). Modelled median event loads are from 88 events a year (2015). Measured median event loads from four wet weather events during 2015-2016.

	Dissolved Zn		**Dissolved Cu**	
	Modelled	*Measured*	*Modelled*	*Measured*
Average	**2814**	**2323**	***44.8***	***83.5***
Minimum		278		*15.9*
Maximum		6869		*299.7*
Contribution from each surface type	*Roofs: 79%* *Roads: 9%* *Carparks: 12%*		*Roofs: 31%* *Roads: 30%* *Carparks: 39%*	

The median pollutant loads for dissolved Zn and Cu that were measured during the four wet weather rain events were very similar to median events loads predicted using MEDUSA (Table 5, Figures 24 and 25). Overall, 2.8 kg dissolved Zn per event were predicted to originate from impermeable surfaces (79% roofs) within the catchment while 2.3 kg dissolved Zn/event of this were measured in-stream. Similarly, 45 g dissolved Cu per event were predicted to originate from impermeable surfaces (39% carparks, 30% roads, 31% roofs) within the catchment comparted to 84 g measured in-stream. Little differences between measured and modelled dissolved metal loads overall highlight two things; (1) the MEDUSA model is effective at predicting the amount and origin of dissolved Zn especially and also dissolved Cu within this catchment and; (2) little immobilisation of these dissolved metals seems to occur downstream from the source since concentrations of dissolved metals were similar. Results from the modelling highlight the likely dominant contribution of dissolved zinc from galvanised roofs and downpipes within the catchment and that carparks produce the most dissolved copper. These findings are substantiate by monitoring of specific surfaces conducted from earlier analysis of the Addington Brook catchment (Charters, 2016).

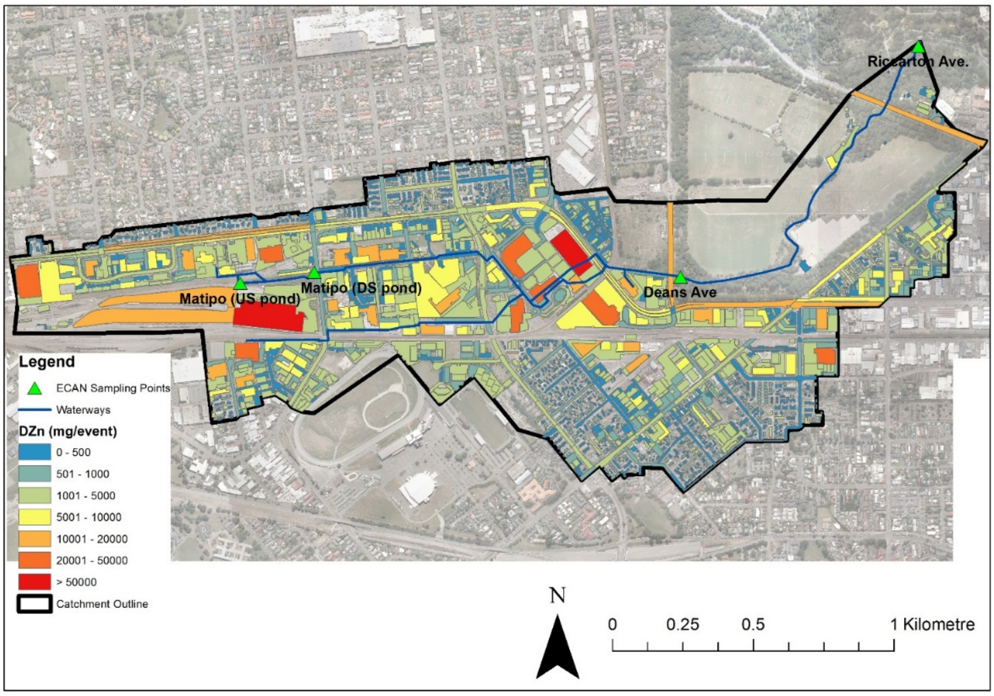


Figure 24. Modelled dissolved zinc (mg/event) from impervious surfaces (roofs/carparks/roads) within the Addington Brook catchment contributing to outlet sampling location at the Riccarton Ave.

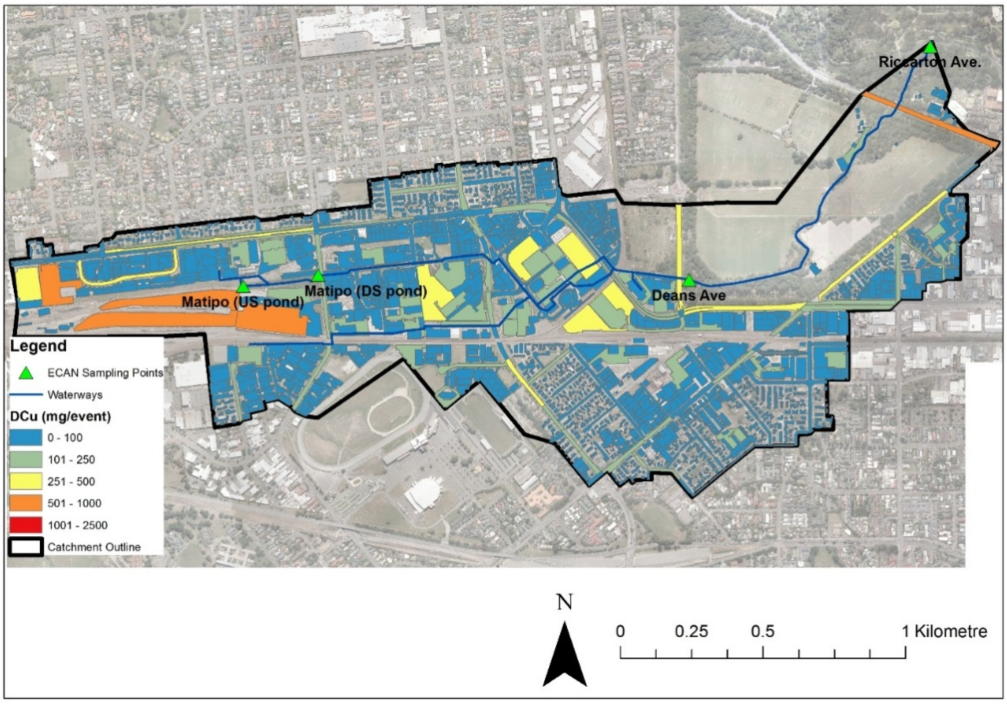


Figure 25. Modelled dissolved copper (mg/event) from impervious surfaces (roofs/carparks/roads) within the Addington Brook catchment contributing to outlet sampling location at the Riccarton Ave.

4. Summary

4.1. Key findings

- Surface water was sampled at all characteristic time points, providing valuable information about the range of concentrations measured throughout each wet weather event at each location.
- Large amounts of TSS enter the Matipo stormwater ponds at the very top of the catchment and are substantially reduced after passing through the ponds but subsequently increase further down-stream of Deans Ave where Addington Brook flows through an open channel before it converges with the Avon River/Ōtākaro.
- TSS concentrations are typically highest during the earlier sampling points at each site, reflecting the initial ('first') flush of solids from impervious surfaces following rainfall. However, concentrations at the receding end of the storm events are still higher at Riccarton Ave (and to a lesser extent Deans Ave) compared to previous years wet weather data.
- Dissolved zinc was consistently and highly elevated above the relevant LWRP guideline throughout the catchment, despite being significantly retained in the Matipo ponds. Concentrations substantially increase down-stream of these ponds with the highest values at Deans Ave, capturing the majority of runoff from the industrial/commercial sector. Large galvanized roof areas in this sub-catchment have shown to contribute very high concentrations of zinc, mainly in dissolved form. While dissolved Zn concentrations are typically highest at the start of a rain event, they remain moderately elevated throughout the storm duration, which may be attributed to their dissolution from galvanized roofs and downpipes for the duration of the rainfall contact time.
- Dissolved copper is removed in the Matipo ponds and is not a major concern downstream in Addington Brook while dissolved lead (Pb) never exceeded the guideline value in any sample.
- Concentrations of TP and TN between years and sampling locations are generally similar, although a consistent pattern seen within the catchment was that these nutrients (along with other key pollutants) are retained within the Matipo pond system but concentrations increase down-stream of its outflow.
- Concentrations of $NH_4^{-}N$ were below the maximum guideline to prevent toxicity to freshwater fish. Higher concentrations were found during the smallest event, which could indicate that the source of ammonium is not related to rainfall runoff, but the exact source of ammonium is undetermined.
- The Matipo ponds were quite effective at removing TSS, even during the largest events, which is most likely attributed to adequate settling potential despite suspected hydraulic short-circuiting.

- Most TP in the stormwater ponds was particulate. Despite the ability of the ponds to significantly reduce TP, DRP concentrations consistently exceeded the LWRP guideline. Targeting solids removal will not be very effective at removing most of the phosphorus concurrently as only a 34% correlation was found.
- TN in the stormwater ponds was comprised mostly of organic TKN. While TN concentrations were significantly removed in the Matipo pond, the inorganic nitrate/nitrate concentrations were sometimes higher during larger rainfall events, suggesting that N in the pond was converted from organic to inorganic fractions through the processes of mineralization and subsequent nitrification.
- The Matipo ponds system is still very effective at retaining dissolved metals with all dissolved metals in the outflow almost consistently below their LWRP guideline values. There was no consistent pattern in inflow metal concentrations as a function of rainfall parameters since longer duration or higher intensity events did not produce greatest metal runoff levels.
- Overall, the Riccarton Ave location transports median loads of 1.808 *k*g/min TSS, 1.75 g/min dissolved zinc, 6.3 *m*g/min dissolved Cu and 7.1 *m*g/min of dissolved lead as well as 37.23 g/min TN and 8.25 g/min TP downstream into the Avon River/Ōtākaro.
- Pollutant loads for dissolved Zn and Cu that were measured in 2015-2016 were very similar to those predicted using MEDUSA highlighting two things; (1) the MEDUSA model is effective at predicting the amount and origin of dissolved Zn especially and also dissolved Cu within this catchment and; (2) little immobilisation of these dissolved metals seems to occur downstream from the source since concentrations of dissolved metals were similar. Results from the monitoring and modelling highlight the dominant contribution of dissolved zinc from galvanised roofs and downpipes within the catchment and that carparks produce the most dissolved copper. These data substantiate similar findings from earlier analysis of the catchment.

4.2. Recommended further work

- Stormwater pipes entering Addington brook near the netball courts of South Hagley Park and on the south side of Riccarton Ave apparently convey substantial suspended solids loads. Therefore, it would be prudent to focus efforts on targeted sampling and pollutant mitigation at the main discharge points at this end of the brook to reduce the amount of solids entering the Avon River/Ōtākaro. It would also be beneficial to understand the amount of particulate metals at these points to enable co-treatment of TSS and particulate metals concurrently. Targeting solids removal will not be very effective at removing phosphorus or nitrogen concurrently so other approaches for removing these nutrients and dissolved metals is needed. Direct input of sediment from eroding stream banks is another potential source worthy of investigation.

- Given the ubiquitous nature of dissolved zinc in Christchurch urban waterways, it would wise to implement source-control of this highly bioavailable metal, especially given dissolved fractions are much more difficult to remove than particulate fractions. Dissolved Zn should be targeted at the Deans Ave location where its concentration is consistently highest and steady throughout the rainfall duration.
- It could be valuable to consider (1) maintenance and; (2) a pollutant tracking exercise for the Matipo pond elements to ascertain their functioning hydraulic retention time, as this time will likely influence the amount of dissolved pollutants (metals and nutrients) that can be removed from diffuse stormwater runoff inputs.
- Comparison of the Matipo ponds treatment performance with that of other stormwater ponds in Christchurch would provide valuable local data for future stormwater pond designs.
- The data in this report represent in-stream mixed concentrations only (water was not sampled directly from pipe discharges), so it is impossible to distinguish between what flowed into the stream during the rainfall events and what may represent some existing (stored) pollutants that may become mobilized when it rains. Sampling from key stormwater pipe discharges and mixed in-stream water at the same time would enable an understanding of the mixing (and dilution) potential of the receiving waterway. Additionally, with flow and concurrent water quality data monitored at other sites in the catchment, it would be possible to compare pollutant loads at the different sub-catchment locations to estimate the greatest pollutant loads to the river system.

5. Acknowledgements

The authors would like to thank Michele Stevenson, Jenny Watters, Lesley Bolton-Richie and Rachel Webster from Environment Canterbury (ECan) for providing the data, their valuable knowledge on the catchment, relevant related reports and peer-review and feedback.

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7. Appendices

Table A1. Sampling time points for the Matipo stormwater ponds with water level

Event	Date & Time	Time point	Rainfall (mm/5 min)	US Level (mm)	DS Level (mm)
1	19-09-15 05:33	1	0.20	363	323
	19-09-15 21:08	2	0.20	577	411
	20-09-15 00:38	3	0.60	738	588
	20-09-15 13:15	4	0.00	357	349
2	11-11-15 18:06	1	0.62	423	325
	11-11-15 18:56	2	0.32	475	356
	11-11-15 23:26	3	0.40	419	348
3	15-01-16 21:41	1	0.00	402	330
	16-01-16 01:06	2	0.00	371	354
	16-01-16 03:06	3	0.00	599	468
	16-01-16 11:40	4	0.00	356	316
4	27-01-16 04:17	1	0.20	441	374
	27-01-16 16:03	2	0.00	477	346
	27-01-16 16:48	3	0.20	671	555
	27-01-16 17:38	4	0.40	644	553
	28-01-16 04:38	5	0.00	610	523
	28-01-16 05:38	6	0.00	405	287

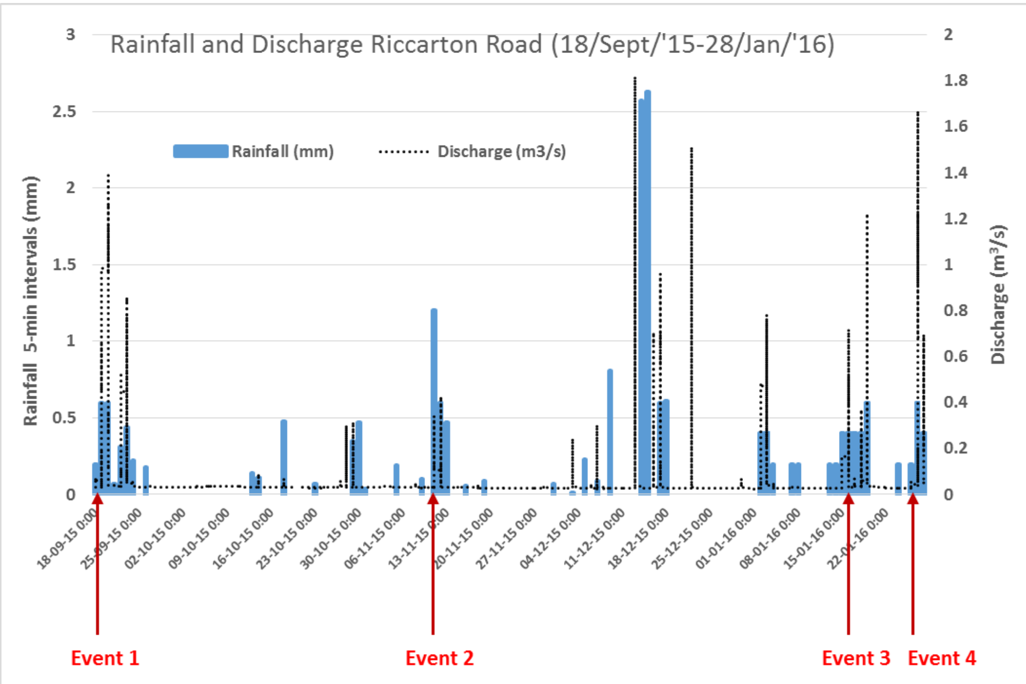

Figure B1. Rainfall and Discharge/Flow Riccarton Ave (18/Sept/'15-28/Jan/'16)

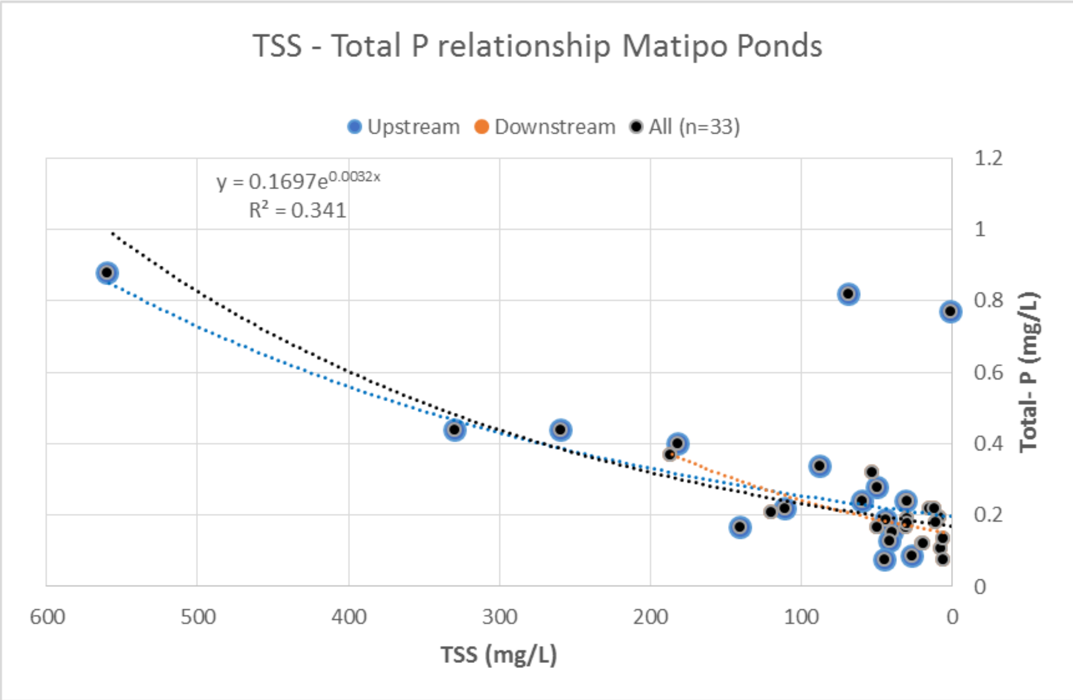

Figure C1. TSS and Total-P relationships for inflow and outflow of pond system.